ERROR ANALYSIS OF A LASER THEODOLITE

BY

James Vincent Dunn, B.S.

The Ohio State University

1966

ERROR ANALYSIS OF THE LASER THEODOLITE

A Thesis

Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by

James Vincent Dunn, B.S.

The Ohio State University
1966

Approved by

Adviser
Department of Geodetic Science

ACKNOWLEDGMENTS

The author expresses his appreciation to Professor Simo H. Laurila for his guidance during preparation of this paper and to every individual who took time from his work to help me in this research. Particular thanks should also be given to Messrs. William Swarner and Frank Jacoby of the Antenna Laboratory, Ohio State University Research Center, Mr. Leslie Cunningham of the United States Naval Oceanographic Office and to Captain William Sprinsky, United States Army.

TABLE OF CONTENTS

ACKNOWLEDGMENTS ii

TABLE OF CONTENTS iii

LIST OF TABLES iv

LIST OF FIGURES v

1 Geodetic Applications of Lasers 1

2 Outline of Laser Theory 6

3 The Laser Theodolite 16

4 Errors 24

4.1 Errors Common to all Theodolites. 26

4.1.1 Uneven Graduations. 26

4.1.2 Dislevelment of the Instrument 26

4.1.3 Horizontal Circle Not Concentric to the Vertical Axis of the Instrument 27

4.1.4 Horizontal Axis Not Perpendicular to the Vertical Axis of the Instrument 28

4.1.5 Lost Motion in the Coincidence System, and Operator's Errors in Setting and Reading the Seconds Drum 28

4.2 Errors Unique to the Laser 32

4.3 The Measurement of Horizontal Angles 49

5 Summary 65

5.1 Errors 65

5.2 Flexibility of Operation 67

5.3 Final System Envisioned 68

BIBLIOGRAPHY 71

LIST OF TABLES

Table

1 Observations to determine the combined effects of lost motion, and setting and reading the seconds drum . . .29

2 Observations of microammeter readings varying with direction 33

3 Observations to determine if there is a difference between readings taken in the clockwise and readings taken in the counterclockwise direction 35

4 Second series of observations to determine if there is a difference between readings taken in the clockwise direction and readings taken in the counterclockwise direction 36

5 Observations made to determine if the shape of the laser beam varies significantly with the alignment of the end mirrors 45

6 Observations taken to determine if the returning signal from a retrodirective mirror depends on the alignment of the mirror relative to the laser 48

7 Observations taken in room 6 of Denny Hall on 21 April 1966. 50

8 Observations taken in room 6 of Denny Hall on 5 May 1966. 57

9 Observations to determine if the laser beam is symmetrical in the vertical plane 64

LIST OF FIGURES

Figure

2.1 Typical energy spectrum of solid laser material . . 10

2.2 Processes in electronically excited gas laser system 12

3.1 Schematic laser theodolite system 17

4.1 Horizontal circle not concentric to the vertical axis 27

4.2 Variation of microammeter reading with direction . 33

4.3 Difference between the mean of clockwise and counter-clockwise observations tabulated in TABLE 3 37

4.4 Difference between the mean of clockwise and counter-clockwise observations tabulated in TABLE 4 37

4.5 Variation of microammeter readings with repetition. 39

4.6 Microammeter reading varying with time under various conditions 40

4.7 Variation of microammeter readings versus directions for various alignments of the laser end mirrors . . 46

4.8 Variation of the returning signal for a change of target alignment of about 45 degrees 48

4.9 Observations of a horizontal angle tabulated in TABLE 7 55

4.10 Observations of a horizontal angle tabulated in TABLE 8 61

4.11 Various laser return signals for selected vertical angles 64

CHAPTER 1

GEODETIC APPLICATIONS OF LASERS

The word LASER is an acroym for Light Amplification by Stimulated Emission of Radiation. The theory of lasers is rather complicated, and will be outlined in chapter 2. The purpose of this chapter will be to briefly describe current research being done with lasers in the field of Geodetic Science. This is necessary for the reader to understand how the laser theodolite, the subject of this thesis, will complement the other tools of the geodesist.

The first working laser was developed in 1961, and in the five years to the present considerable research has been done with lasers. The field that has received the most attention has been communications. As an example, all of the news media covered the laser communication experiment conducted incident to the Gemini 6 space mission in December of 1965. Work has also been done in such diverse fields as medicine and welding. Although the field of geodesy is not being as intensly researched as the fields of communications or medicine, the work being done with lasers is significant, and should be cited.

The purpose of the work of Reese [1] was to review systems

developed for ground to ground surveying utilizing lasers. For more complete information the reader is referred to Reese's work, or to original sources of the various agencies. He also discussed the theoretical ranging limits of a laser ranging device. Reese came to the conclusion that a geodetically accurate ranging device could be designed with a maximum range of eighty kilometers. He assumed a one milliwatt, continuous wave, gas laser was used. This seems to be a modestly powered laser, and his other parameters were reasonable. A listing of laser systems being developed will now be made.

The U. S. Navy Electronics Laboratory received a geodetic laser ranging system from Lear Siegler, Inc. in March of 1964. The laser is of the water cooled, ruby crystal type, and is mounted in an invar block. To the date of Reese's paper about twenty thousand firings have been made, but no results have been published. However, the information available seems to indicate that the early development of a reliable ranging system is likely.

The U. S. Coast and Geodetic Survey and the National Bureau of Standards, working jointly, have replaced the mercury vapor light source of a model 4D Geodimeter with a gas laser, and have conducted some experimentation. Results to date have given reason to believe that the accuracy of the system has been improved, although experimentation has not

been extensive enough to give definitive results. The AGA corporation performed a similiar experiment. However, they discontinued work when a survey of customers indicated that the added expense of the laser was not warranted.

The Hughes Aircraft Company has developed a system called COLIDAR for Coherent Light Detection And Ranging. This system is designed for military uses, and, as such, has not been designed for geodetic accuracy. However, in Reese's opinion, this system could be improved to geodetic accuracy. Similar systems have been announced by Raytheon, RCA, Autonetics, Fort Monmouth and Frankford Arsenal.

The Ohio State University Antenna Laboratory has done some ranging experiments with a pulsed laser system in conjunction with a U. S. Navy sponsered underwater communications system. As with the Hughes Aircraft Corporation COLIDAR system geodetic accuracy was not attempted.

The Air Force Cambridge Research Laboratories conducted a ranging experiment in 1963 using a pulsed ruby laser, and measured the distance between two buildings as one hundred yards with an accuracy of one yard. Although no return was received, the laser was visible at 32.95 miles. According to Reese further research has been done, but no results have been published.

Research has not been confined to the United States. As an example, in Great Britain, and at the French Laboratoire

de Télécommunications, separate ruby laser rangefinder systems have been developed. The accuracies of these systems were not knowm by Reese.

This listing of research projects shows that the idea of a geodetic laser ranging device is generally considered feasible, and it will be assumed that such a system will be available commercially in the near future. This system will undoubtedly be of considerable value to a geodetic survey party. However, it will still have drawbacks. One disadvantage will be that only ranges will be available. With only ranges the network can be constructed using trilateration techniques. There is a possibility that a small systematic error, such as a slightly inaccurate index of refraction, that is of negligible importance in one line, may propagate to an unacceptable degree over the network.

One way to provide a check on systematic errors would be to supplement the ranges with angular measurements. In some of the systems under development already cited an optical telescope is used for sighting on the target simultaneously with the laser beam ranging. One disadvantage of this is that the laser target may be too large for fine bisection, and accuracy may be lost. Another disadvantage would be that full utilization of the laser's ability to operate under adverse (compared to optical systems) conditions would not be gained. This might significantly increase the time required to complete a survey.

One way to avoid this linking of the laser ranging system to an optical angle measuring system would be to use the laser to measure angles. As far as the author was able to determine this idea was first proposed by Cunningham. [2] A brief description of the laser theodolite as designed and constructed by Cunningham will be given in chapter 3.

The purpose of this paper will be to determine the sources of errors in the theodolite as constructed by Cunningham. If this is done this paper will be of considerable value in designing a laser system for the simultaneous measuring of ranges and angles.

CHAPTER 2

OUTLINE OF LASER THEORY

This paper will not attempt to describe laser theory, but will just briefly summarize some salient points. A definition of a laser may be given as, a device used as a source of nearly monochromatic light that may be focused with an extremely narrow beamwidth. The order in which material will be given is; a discussion of molecular and ion energy levels, and summaries of Planck's Law, the phenomena of spontaneous emission, and excitation.

Let the term particle refer to molecules, atoms, or ions. Any particle will have an internal energy level that will be a function of the orientation and motion of the particle, and of the components of the particle. In motion we would even have to include the rotational velocities of the various nuclei and orbital electrons. One theory is that there are, generally speaking, definite and distinct energy levels for any particular substance. Another way of saying the same thing is that a particle may not take any random orientation and motion. There are only certain orientations and motions that a particle may take. A collorary of this is that there are only a finite number of energy increments that may be emitted or absorbed by any particular particle. This principle, that there are only a finite number of energy levels that a particle

may have, has been borne out by experimentation.

The most basic principle in understanding the laser was proposed by Max Planck in 1900. Planck proposed the quantum theory, holding that radiant energy, such as light waves, consists of definite, elemental quantities of energy. He also considered the electron as an electronic oscillator that can emit only whole quanta (or whole units of energy). He also held that the frequency of the radiation was a direct function of the energy emitted by the particle.

Consider the elementary particle consisting of one or more nuclei and any number of orbital electrons. This particle will be at a definite energy level, dependent on its motion and orientation, denoted by EL1. Now let the particle go to some lower energy level, denoted EL2, by radiating electromagnetic energy. EL2 will also depend on the particle's orientation and motion. Planck's law, mathematically, would be:

$$EL1 - EL2 = h \cdot f$$

where h is Planck's constant and

f is the frequency of the emitted radiation.

Therefore, the frequencies obtainable from a specific material are limited, since the number of energy levels are limited. There will be one frequency for each possible transition between the various energy levels. This fact describes, to a great extent, the temporal coherence of a laser beam. Temporal coherence is the degree with which electromagnetic energy from

a source approaches a single frequency. Actually, a laser does not emit a single frequency, but has a definite bandwidth, as the energy levels are never perfectly sharp. This may be explained by reasoning that at one energy level there can be only one specific orientation and set of velocities. This is not quite correct in that it would be better to say that there is a narrow energy spectrum that the particle may take. As an example, for one specific energy level the nucleous of the particle must have one definite rotational velocity. Actually, the nucleous can take a rotational velocity within a narrow range. Therefore, the energy level is not perfectly sharp. The laser does approach a monochromatic light source.

In a laser there are two sources of radiation, consisting of induced radiation, and spontaneous radiation. The spontaneous emission is a natural occurrence independent of any applied radiation field. In a maser, operating at microwave frequencies, the energy transitions are small, and the enclosures containing the active maser material have dimmensions comparable with the wavelength of the emitted radiation. Both these factors tend to make spontaneous emission almost negligible. With the laser, the difference between the energy levels is comparatively large, and the active material is usually very large in relation to the wavelength of the emitted radiation. Spontaneous emission

in a laser cannot be considered negligible. One way to minimize the amount of spontaneous emission is to choose a propagating structure which supports only a few modes, and the second is to use mode selection techniques in the enclosure, so that amplification occurs only in the desired modes, and other modes are rapidly lost from the system. A combination of both approaches is possible. [3] In amplification it must be understood that there are many, or may be many, energy levels at which the particle may be. As an example, there may be, in decreasing order, energy levels a, b, c, and d, at which the particle may be. There will then be the following mode possibilities; f1, a to d; f2, a to c; f3, a to b; f4, b to d; f5, b to c; and f6, c to d. For a monochromatic light source, and for maximum efficiency, all radiation should be at one frequency.

There are presently available two methods of excitation of the laser material. A laser radiates energy in the form of light, and some energy losses as heat, and other, invisible, electromagnetic radiation. Obviously, this energy must be put into the laser in some manner. These two methods of excitation will now be briefly described.

In solid lasers the usual excitation is optical energy. A suitable crystal is found possesing an absorption spectrum of the type represented by figure 2.1. Atoms may be excited

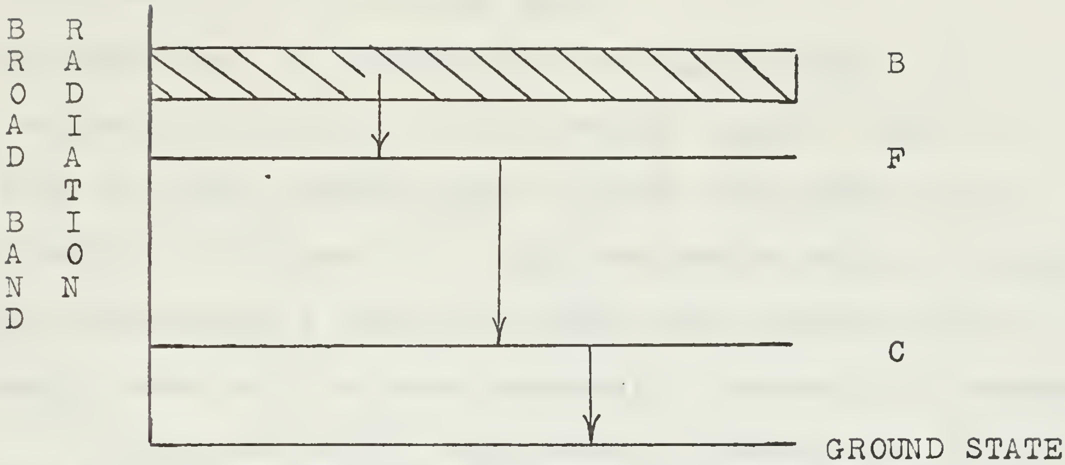

Fig. 2.1. Typical energy spectrum of solid laser material.

by absorption of incident, optical, radiation to the broad band B from which they make non-radiated (ie., thermal) transitions to the sharp fluorescent level F. From here, the return may be directly to the ground state, as occurs in the ruby optical maser or to the lower thermal level C, lying at a reasonable energy gap from the ground state. Almost all solid state systems operate by the latter mechanism. [4] The particles at energy level C are thermally cooled to the ground state. The reason that state C is desirable is beyond the scope of this paper. Briefly, laser action will only occur if there are more excited particles than non-excited particles. With the intermediate step it is more easy to keep the number of particles at F greater than the number at C, as the particles at the ground state are not part of the ratio. Without the intermediate step the ratio would be the number

at C to the number at the ground state.

Gas lasers may be manufactured on the principles of optical excitation similiar to the crystal laser. This is seldom done as gases seldom exhibit broad band energy levels such as level B of figure 2.1. Thus the system must be excited by a near monochromatic source of light that corresponds to a sharp energy level of the laser material. According to Heavens:

> "The more widely used method of excitation of gas systems entails establishing a glow discharge in the gas, either between electrodes, using a direct current, or by the use of a high frequency source, capacitively coupled. The latter method has the advantage that there are no metal electrodes inside the laser tube and hence no danger of sputtering by the gas discharge. When internal electrodes are used, as in the direct current system, these are positioned in side tubes, clear of the discharge region. The situation in such a system is highly complex, as is illustrated by figure 2.2 (Heavens' figure number 5,5), taken from Fowler's article in the Handbuch der Physik. In general, the distribution of energy levels of the various particles present in a discharge will not be Maxwellian and the steady state equilibrium in which a population inversion obtains derives from the interplay of different processes, each with its own non-thermal equilibrium distribution. . . . For a complete understanding of the behaviour of a gas under discharge conditions, it is essential to know the cross-section for all the processes indicated in figure 2.2. This information is never available in sufficient detail but it can sometimes be arranged that the effects of the possible processes are minimized." [4]

As seen from the quotation from Heavens the practical applications of electronically excited gas lasers are quite complicated, and more in the field of the electronics engineer or the physicist, than the geodesist. Before concluding this chapter one last property of the laser should be mentioned. By

[illegible]

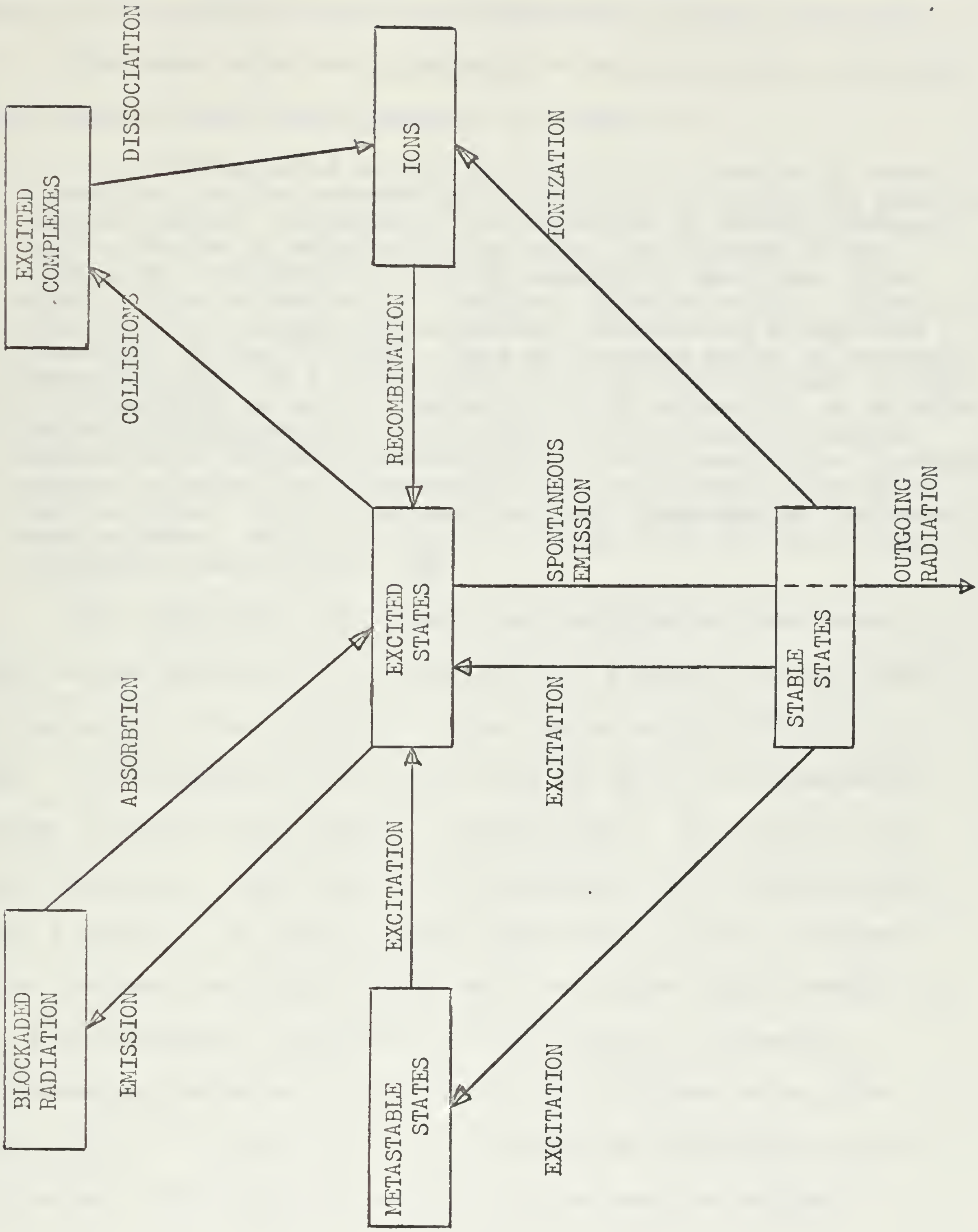

Fig. 2.2. Processes in electronically excited gas laser systems.

an application of Planck's Law a laser has temporal coherence, that is, the emitted radiation approaches a single frequency.

The laser also has a property known as spatial coherence. This property has been discussed by Schawlow.

> "Stimulated emission, which is the basis of maser operation, is the reverse of the process in which the electromagnetic waves, or photons, are absorbed by atomic systems. When a photon is absorbed by an atom, the energy of the photon is convertrd to internal energy of the atom. The atom is then raised to an 'excited' quantum state. Later it radiates this energy spontaneously, emitting a photon and reverting to the 'ground' state or to some state in between. During the period in which the atom is still excited it can be stimulated to emit a photon if it is struck by an outside photon having precisely the energy of the one that would otherwise be emitted spontaneously. As a result the incoming photon, or wave, is augmented by the one given up by the excited atom. More important and more remarkable, the wave, upon release, falls precisely in phase with the wave that triggered its release." [5]

This means that the laser beam has spatial coherence. This may be defined as a characteristic whereby the amplitude of the wave at one instant of time varies sinusoidally with time. What happens in the gas laser is that electromagnetic energy increases the internal energy level, or excites, the laser material. Then one of the particles will spontaneously emit a particle of light energy that will, in turn, trigger other excited particles, which will emit more light energy, at the same frequency and phase as the initial, triggering, spontaneous, emission. This wave will propagate along the long axis of the laser until it reaches an end mirror, and is reflected. The returning wave will continue to trigger

further excited particles. If the increase in the wave equals the power losses at the end mirrors a steady, standing wave will be set up. If the increase in power of the wave is greater than the losses, then part of the wave can be tapped as a usable output.

This briefly describes some laser theory. No attempt has been made to describe the laser mathematically, or to describe some many important features, such as why it is necessary to have a ratio of excited to unexcited particles greater than unity, and how this is done. However, as said before, this is in the field of the electronics engineer or the physicist.

For the geodesist the most interesting features are the degree of spatial coherence and temporal coherence posessed by the laser beam, and its extremely narrow beamwidth. These characteristics make the idea of a laser theodolite feasible in theory. Its extremely narrow beamwidth makes it possible to hope that we can get geodetically accurate angular measurements, as the pointing will be with an almost well defined line rather than an electromagnetic "lobe". The characteristic of the extremely narrow beamwidth also increases theoretical ranges of a ranging device. The spatial coherence of the laser beam should increase the accuracy of interference measurements. The temporal coherence of a laser beam will permit the determination of the index of refraction corrections

[illegible]

[illegible]

[illegible]

to field observations to be much more precisely made. In fact, research with lasers, due to the temporal coherence of lasers, in other branches of science, may lead to more precise determinations of physical parameters associated with light.

CHAPTER 3

THE LASER THEODOLITE

As mentioned in chapter 1 the laser theodolite was first proposed, and then designed and constructed by Leslie Lee Cunningham in late 1965. This chapter will not attempt to duplicate the details of construction given by Cunningham. [2] This chapter will identify the components of the laser theodolite, and will list the advantages and disadvantages of those components.

To introduce the laser theodolite figure 3.1 is included. Basically, this system consists of a standard theodolite, with a laser replacing the telescope, and a power supply (a battery), DC-DC converters, and a photomultiplier tube to detect returning signals.

The largest component of the laser theodolite system, physically, is the base. This is the base of a Wild-Heerbrugg T-4 Theodolite. This was decided upon by reason of availability. The pointing telescope, the hanging level, and the vertical circle were lost in the Southwest Pacific. The base was then donated for the period of this test by the U. S. Naval Oceanographic Office. This component is a first order instrument, and any

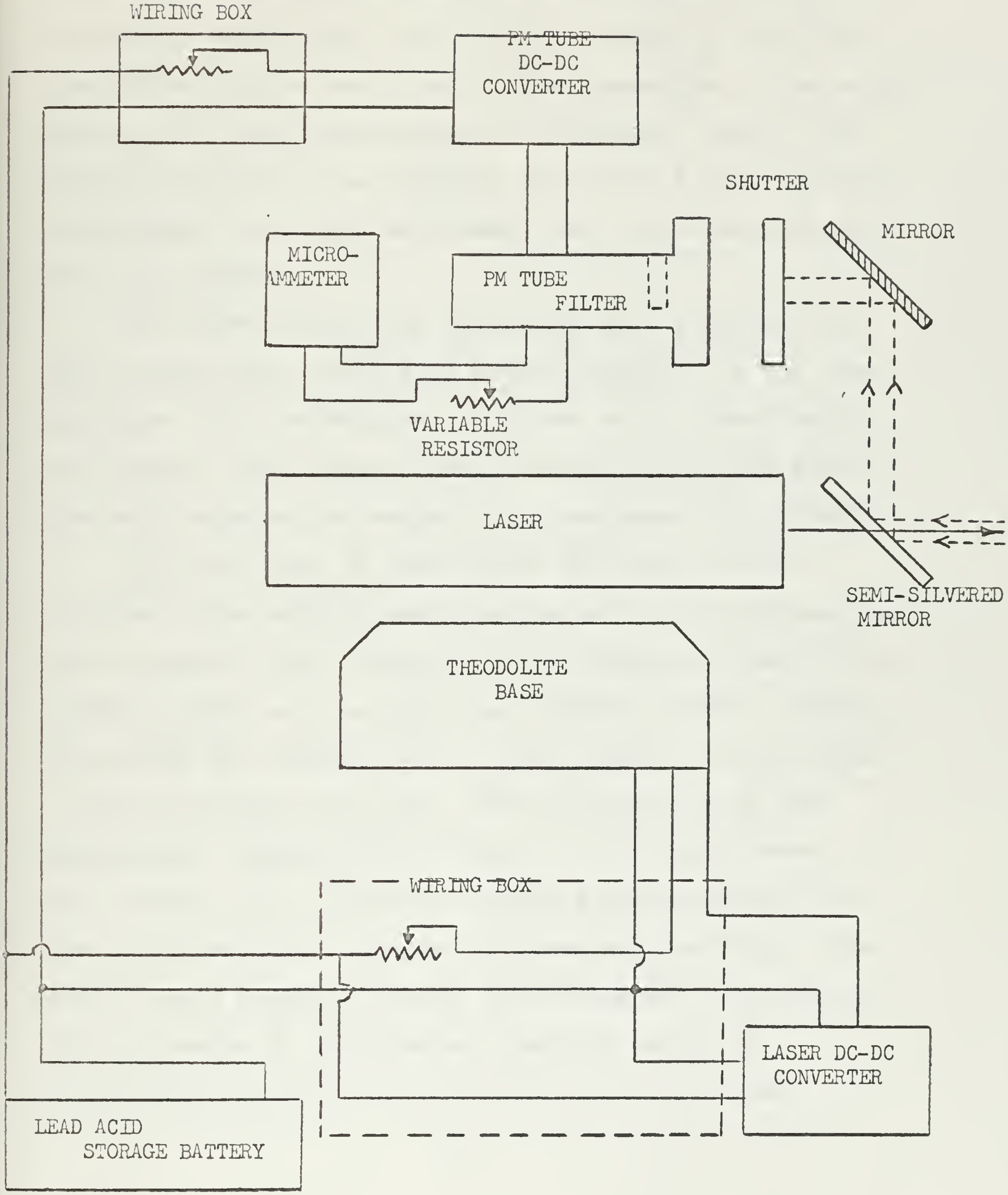

Fig. 3.1. Schematic laser theodolite system.

future laser theodolite should be of similiar quality. Since part of the base was lost, the testing of the laser theodolite will be restricted to the measuring of horizontal angles, with the targets near the horizontal plane. This should not prove to be a severe limitation for the purpose of testing, and it can be assumed that the production model will be complete.

The power source for the system is a standard six cell, twelve volt, lead acid storage battery, of the same type used in an automobile. A silver zinc battery would be lighter, would require fewer chargings, and may warrant the added expense for reason of convenience in the field.

For the laser in this system the plate circuit requires three hundred twenty volts, and sixty milliamperes, direct current, and the grid circuit requires seven and two teenths volts, and one and a half amperes, direct current. To step up the twelve volts to three hundred twenty volts a DC-DC converter was used. This was produced by the ELECTRONICS RESEARCH ASSOCIATES, Inc., of Cedar Grove, New Jersey, and is their ERA TRANSPAC model number TC131. The output of this converter is three hundred fifty volts, and it has a maximum capacity of one hundred milliamperes. This converter is satisfactory, but the output is unregulated. Before the production model of a laser

theodolite is designed an electronics engineer should decide if the added expense of a regulated converter is warranted. The three hundred fifty volt output is stepped down to three hundred twenty volts through a fixed resistor. The twelve volt battery output is stepped down to seven and two tenths volts through another resistor.

An integral component of the laser theodolite system is a photomultiplier tube for the detection of returning signals. The DC-DC converter for the photomultiplier tube was manufactured by INDUSTRIAL LABORATORIES, of Fort Wayne, Indiana, a division of International Telephone and Telegraph, Inc., and is their model IL2-1800. This converter has a six volt, direct current, input and an unregulated one thousand six hundred volt, direct current, output.

The photomultiplier tube used is an RCA Development Type, Dev No C70042C. The PM tube can be operated at any voltage between eight hundred and two thousand two hundred volts, direct current, and is most efficiently operated at one thousand five hundred volts. It is intended for use in applications requiring the detection of low light levels, and is recommended for use in laser detection to eight thousand angstroms. The wavelength of maximum response is four thousand two hundred angstroms. The output of the PM tube is lead to a variable resistor, and then to a zero to fifty microammeter. The one megohm variable resistor

is placed in series with the ammeter to protect the ammeter from high currents encounted from strong returning signals. The ammeter is used either to determine the direction of the peak returning signal, or to see that the same intensity is received from either side of peak intensity.

One last piece of auxillary equipment associated with the PM tube is an optical interence filter manufactured by the BAIRD ATOMIC Inc., of Cambridge, Massachusetts, and is their model B-12. For possible use in daylight some method had to be used to protect the PM tube. The filter has a peak wavelength of 6565 angstroms, a one-half bamdwidth of 9 angstroms, a one-tenth bandwidth of 28 angstroms, and a peak transmission of 37%. Since the laser has an operating frequency of 6328 angstroms this filter cannot be used in this system. There still is a filter requirement in the laser theodolite, but the filter must be matched to the laser's operating frequency.

The laser is the ELECTRO OPTICS ASSOCIATES, of Palo Alto, California, model EOA-LAS-101. It has an output of one milliwatt at a wavelength of 6328 angstroms. Two excellent features of this laser are; firstly, the four operating plasma tubes are operated in parallel electrically and in series optically, and, secondly, the Brewster Windows are made of glass. Arranging the plasma tubes in parallel electrically eliminates the principle hazard

that is inherent in all directly excited gas lasers; that of the presence of voltages exceeding one kilovolt, which require high voltage safety precautions. The use of glass Brewster Windows, rather than fused silica windows, reduces the gain at the strong 1.15 and 3.39 He-Ne transitions, which produce an invisible output light. Refering to figure 2.2 it can be seen that there is likely to be unwanted transitions in any gas laser. This model laser has less desirable features that should be mentioned. Firstly, the overall length of the laser is fifteen inches. This is objectionable because the theodolite cannot be reversed due to the length of the laser. This would, of course, be eliminated in a production model. Secondly, the end mirrors of the laser are supported, not to a relatively protected item, such as the laser plasma tubes, but to the cover of the instrument itself. The alignment of the end mirrors to be mutually perpendicular to the optical axis of the laser is a critical adjustment. If either mirror is not perpendicular to the axis of the laser there will be no internal reflections and consequently no laser action. The reason that the end mirrors are not in a more protected position is that the instrument was not designed for field use. "Due to its simplicity of operation and construction, the LAS-101 is ideally suited as a compact source of visible, coherent light. . . . The LAS-101 can be used on the table

[illegible]

or laboratory bench, and is easily adaptable to all optical bench mounts." [6] In addition, the PM tube, the PM tube DC-DC converter, the microammeter, and the variable resistor across the PM tube output have all been secured to the cover of the laser. This undoubtedly causes torques on the cover, to which the end mirrors are indirectly attached, and no design provision was made for this. The net result is that the end mirrors need constant, tedious realignment. Thirdly, as provided by the manufacturer the LAS-101 has an uncollimated beam divergence of thirty arc minutes. Unfortunately, Cunningham was not able to procure a set of collimating lenses for the laser due to time and money limitations. This will cause a serious range loss in the system that can be avoided in a production model. This will also adversely affect the accuracy of the system. The beam of light, without collimating lenses, will be less well defined than it would be with collimating lenses.

Since retrodirective target mirrors were used as target mirrors, the returning signal will, in effect, not be centered on the PM tube orifice, but rather on the laser. To overcome this Cunningham designed a beamsplitter from salvage material. However, the beamsplitter has no degrees of freedom, making alignment difficult. The rated power loss through the semisilvered mirror is fifty percent. A

better solution would be to use an ordinary mirror with an hole in the center for the transmitted signal from the laser. Although part of the returning signal would be lost at the hole, if the dimensions of the hole are small, this loss would be more acceptable than a fifty percent loss of the transmitted signal. The beamsplitter also requires some method of alignment short of disassembly.

The target used in this system is a geodimeter corner reflector manufactured by BERG, HEDSTROM and COMPANY. This is an excellent component of the system. There is no way to plumb the target mirror over a point on the ground. This will have to be corrected in a production model.

This has not been a complete discussion of the Cunningham Laser Theodolite. The reader is referred to his work for a more detailed review. No mention has been made of the several wiring boxes that have been constructed as components of the system.

CHAPTER 4

ERRORS

The purpose of this thesis is to investigate the laser theodolite to determine if it will meet geodetic requirements of accuracy in angle measurements. From the partial listing of the various agencies working to develop a laser ranging system it seems obvious that a satisfactory ranging system will soon become operational. The second generation system will then be a laser system that will give range and azimuth, and possibly vertical angle information, to a target in one setup. The utility of such a system in photogrammetric applications is obvious. Since ranges as well as directions would be measured it may even be possible to establish a geodetic network that is stronger than a conventional first order network.

Although vertical angles were mentioned in the above paragraph, no investigation will be made. There are three reasons for this. First, and foremost, there is no vertical circle on the instrument. Second, there is no precision level on the instrument. Third, the vertical lock is not satisfactory. For these reasons only horizontal angles will be investigated. One more limitation must be mentioned. Due to the instrument's instability, or possibly operator's

[illegible]

ineptness, the author was unable to obtain satisfactory results out of doors. Therefore, observations were made only in room 6 of Denny Hall. Since ranges were short, centering errors will be critical. The usual way to determine the error of a horizontal angle would be to measure the angle with the system being tested, and then measure the angle with a theodolite of known accuracy a sufficient number of times to be sure that the mean is approching the true value of the angle. Due to the short ranges that were encountered, this will not work. At short ranges the centering errors will be larger, possibly, than the difference between the two measurements of the angle. Therefore, the repeatability of observations will be taken as a measure of truth, which seems to be an unavoidable assumption.

The remainder of this chapter will be a discussion of the errors encountered in the laser theodolite. These errors fall naturally into two classes. The first class will be errors that are common to all theodolites. The second class will be errors that are peculiar to a laser system.

4.1. ERRORS COMMON TO ALL THEODOLITES

4.1.1. Uneven Graduations

Uneven circle graduations of both the horizontal circle and the seconds drum can cause a systematic error in the measurement of horizontal angles. Normally both are advanced between repetitions so as to average out the error due to uneven graduations. This should also be done with a laser theodolite. In a first order theodolite this is not a serious problem, and there is no reason to believe that this would be a problem with a laser theodolite. This was not done in this work for a reason. When they are advanced between repetitions the initial direction is set to zero, and the variations between the repetitions are all taken in subsequent directions. For the purpose of this paper, it is easier to visualize the variations as they really are, that is, without setting any direction to zero. This procedure may be the cause of some systematic error, but with a first order instrument like the T-4 it should be small. Since repeatability is being taken as a measure of truth this error will not be apparent in the results obtained.

4.1.2. Dislevelment of the Instrument

If the instrument is out of level by an amount i", the error of a direction will vary in magnitude from zero to i"tan.(h), where h is the elevation of the target. This error will not cancel with a change of face. Allied to this problem is the

error caused by a lack of parallelism between the horizontal circle and the instrument's level. With proper field procedures this cause of error can be eliminated. The laser theodolite would require the same procedure. Except for astronomical work geodetic targets are normally at small vertical angles and this problem of dislevelment of the instrument has been reduced to acceptable limits. Assuming that the production laser theodolite has a precision level of a quality comparable to a normal geodetic theodolite, and the same care is exercised in leveling the instrument, this will not be a significant problem in a laser ranging and angle measuring system.

4.1.3. Horizontal Circle Not Concentric to the Vertical Axis of the Instrument

Referring to figure 4.1 it can be seen that the error arising from the horizontal circle not being concentric to the vertical

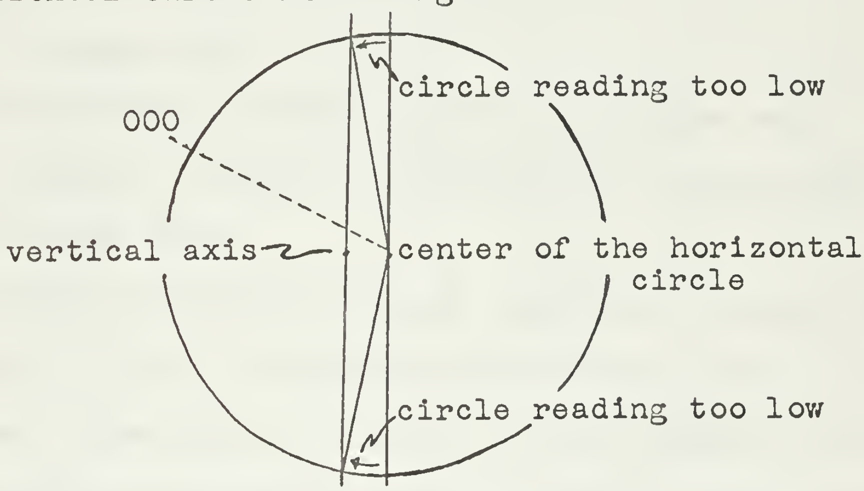

Fig. 4.1. Horizontal circle not concentric to the vertical axis

axis of the instrument will be self canceling if the instrument is of the double vernier type. The Wild T-4 is of this type, and a production model should also incorporate this feature. If the double verniers are not located exactly one hundred eighty degrees apart an error will be introduced in a direction measurement. However, every direction will be wrong by the same amount, and no error will be introduced in an angle measurement deduced from two directions.

4.1.4. Horizontal Axis Not Perpendicular to the Vertical Axis of the Instrument

If the horizontal axis differs from the normal to the vertical axis by an angle i", the error introduced by taking a direction to a target at elevation h may be as large as i" tan.(h). This error is cancelled with a change of face. Since the Cunningham Laser Theodolite cannot be reversed it is subject to this error. A production model of the laser theodolite will have the ability to change face.

4.1.5. Lost Motion in the Coincidence System, and Operator's Errors in Setting and Reading the Seconds Drum

These three errors are present in any theodolite and are difficult to differentiate. Table 1 includes measurements made in three different cases. Case one is a series of one hundred observations taken always moving the micrometer milled head in the clockwise direction. Case two is a series of observations made by moving

[illegible]

TABLE 1. - - Observations to determine the combined effects of lost motion, and setting and reading the seconds drum

Observations taken in the clockwise direction.

22".38	.22	22".10	-.06	22".58	.42	21".82	-.34	21".72	-.44
22.70	.54	21.68	-.48	22.60	.44	21.45	-.71	22.28	.12
22.50	.34	22.42	.26	22.25	.09	21.81	-.35	21.72	-.44
22.92	.76	22.31	.15	21.40	-.76	22.00	-.16	21.68	-.48
22.61	.45	22.30	.14	21.30	-.86	22.01	-.15	21.52	-.64
22.76	.60	22.22	.06	22.72	.56	22.45	.29	21.92	-.24
22.39	.23	22.10	-.06	22.20	.04	21.80	-.36	22.10	-.06
22.19	.03	22.45	.29	22.05	-.11	21.80	-.36	21.72	-.44
22.18	.02	22.32	.16	22.00	-.16	21.69	-.47	22.42	.26
22.49	.33	22.15	-.01	22.40	.24	22.60	.44	22.50	.34
22.80	.64	21.60	-.56	22.28	.12	22.10	-.06	21.64	-.52
22.37	.21	22.25	.09	22.24	.08	21.70	-.46	21.85	-.31
22.24	.08	22.21	.05	22.50	.34	22.50	.34	22.35	.19
22.46	.30	22.30	.14	22.10	-.06	22.20	.04	21.89	-.27
22.65	.49	22.10	-.06	22.10	-.06	22.22	.06	22.12	-.04
22.72	.56	22.21	.05	22.10	-.06	21.82	-.34	22.10	-.06
22.28	.12	22.60	.44	22.45	.29	22.00	-.16	22.08	-.08
22.05	-.11	21.94	-.22	22.20	.04	21.89	-.27	22.31	.15
22.25	.09	22.20	.04	22.12	-.04	21.70	-.46	22.12	-.04
22.61	.45	22.10	-.06	22.15	-.01	22.10	-.06	22.10	-.06

Mean value of 100 observations 22".16
Standard error of a single observation ±.33

Observations taken in the counterclockwise direction

23".20	1.22	22".15	.17	21".55	-.43	21".08	-.90	21".68	-.30
23.22	1.24	22.00	.02	21.98	0	21.00	-.98	21.30	-.68
22.00	.02	22.34	.36	22.21	.23	21.31	-.67	21.35	-.63
22.97	.99	21.92	-.06	21.91	-.07	21.31	-.67	21.42	-.56
23.19	1.21	22.49	.51	21.70	-.28	21.95	-.03	21.69	-.29
22.80	.88	22.81	.83	21.90	-.08	21.42	-.56	21.98	0
22.59	.61	21.82	-.16	21.40	-.58	21.80	-.18	21.54	-.44
22.20	.22	21.55	-.43	21.39	-.59	22.05	.07	21.62	-.36
22.26	.28	21.98	0	21.80	-.18	22.10	.12	21.80	-.18
22.90	.92	21.94	-.04	21.70	-.28	21.90	-.08	21.96	-.02
22.49	.51	21.82	-.16	22.20	.22	21.92	-.06	21.79	-.19
22.64	.66	22.19	.21	22.30	.32	22.10	.12	21.30	-.68
22.89	.91	22.18	.20	21.35	-.63	21.62	-.36	21.30	-.68

TABLE 1. - - Continued

22".08	.10	22".25	.27	21".70	-.28	21".70	-.28	21".78	-.20
22.90	.92	22.12	.14	21.65	-.33	22.21	.23	21.70	-.28
22.48	.50	21.90	-.08	21.78	-.20	22.03	.05	22.41	.43
22.42	.44	21.72	-.26	21.59	-.39	21.52	-.46	22.25	.27
22.36	.38	21.92	-.06	21.35	-.63	22.40	.42	21.53	-.45
22.80	.82	21.56	-.42	21.68	-.30	21.60	-.38	22.25	.27
22.48	.50	21.88	-.10	21.98	0	21.63	-.35	22.01	.03

Mean value of 100 observations 21".98
Standard error of a single observation ±.48

Observations taken in a random manner

22".45	.43	22".26	.24	21".82	-.20	21".90	-.12	21".32	-.70
22.25	.23	21.74	-.28	21.73	-.29	21.60	-.42	21.70	-.32
22.70	.68	22.45	.43	21.11	-.91	21.50	-.52	21.90	-.12
22.46	.44	21.98	-.04	22.00	-.02	21.92	-.10	21.92	-.10
22.32	.30	22.34	.32	21.70	-.32	21.70	-.32	22.10	.08
22.32	.30	22.31	.29	22.08	.06	22.22	-.20	21.70	-.32
22.40	.38	22.31	.29	22.15	.13	22.15	.13	21.72	-.30
22.40	.38	22.10	.08	22.40	.38	22.08	.06	21.89	-.13
22.48	.46	22.32	.30	21.99	-.03	22.01	-.01	21.88	-.14
22.46	.44	22.67	.65	21.30	-.72	21.50	-.52	21.95	-.07
22.22	.20	22.01	-.01	21.89	-.13	21.78	-.24	21.70	-.32
22.11	.09	22.00	-.02	22.02	0	21.88	-.14	21.55	-.47
22.02	0	22.12	.10	21.91	-.11	21.94	-.08	21.80	-.22
22.78	.76	22.42	.40	21.90	-.12	22.31	.29	21.88	-.14
21.90	-.12	22.11	.09	22.05	.03	21.91	-.11	21.90	-.12
22.80	.78	21.78	-.24	22.01	-.01	21.99	-.03	21.58	-.44
22.49	.47	22.21	.19	22.05	.03	21.91	-.11	21.90	-.12
22.38	.36	22.21	.19	21.91	-.11	21.55	-.47	21.70	-.32
22.54	.52	21.72	-.30	21.80	-.22	22.15	.13	21.85	-.17
22.45	.43	22.10	.08	21.42	-.60	21.90	-.12	22.15	.13

Mean value of 100 observations 22".02
Standard error of a single observation ±.33

the micrometer milled head in the counterclockwise direction. The third series of observations was made moving in an irregular manner, either clockwise or counterclockwise, until coincidence was achieved. During the observations the instrument was not moved, and the horizontal clamp was engaged. In other words, the instrument was under identical conditions, and an identical reading should have been made every time. The readings were made in groups of twenty repetitions, even though they are tabulated in groups of one hundred. There is no indication that the instrument moved during the observations. The difference between the mean of the readings in the clockwise direction, and in the counterclockwise direction, of almost two tenths of a second can only be explained by lost motion in the T-4. The procedure used in the field with a production model of the laser theodolite will have to eliminate this cause of error. The Wild T-4 has a seconds drum that is too easy to read to be a large factor in the magnitude of the standard errors observed. The smallest standard error was in the set of observations made in a random manner. ($\pm 0\overset{''}{.}328$ rounded to $\pm 0\overset{''}{.}33$) This indicates that the operator needs practice in achieving coincidence.

4.2 ERRORS UNIQUE TO THE LASER

Section 4.1 briefly described the errors in the Cunningham Laser Theodolite that are common to all theodolites. For the reason that these errors are well understood little detail was given to them. In this section, since the material does not correspond to conventional theodolites, considerable detail will be given.

The first experiment conducted was to determine the magnitude of the returning signal from the target, retrodirective mirror. The microammeter was read at a number of directions at equal intervals as the laser was trained across the target, The observations were made in room 6 of Denny Hall. The background light was controlled, and did not change during the observations. The temperature and humidity also did not change. The PM tube shutter, and the variable resistor across the PM tube output, were not varied. The results of this series of observations are given in TABLE 2, and illustrated in figure 4.2. The directions are from an arbitrary point. The first, and obvious, conclusion is that the laser beam is not symmetrical. This could be a source of systematic error, but does not necessarily mean that the idea of a laser theodolite is impractical. Provided that the same relative point on the curve from one target was compared to the relative point on the curve from a second target no error would be introduced. The procedure

TABLE 2. - - Observations of microammeter readings varying with direction.

Directions are in minutes and seconds. Current is in microamperes.

00'00"	6.0	06'30"	30.6	13'00"	25.5	19'30"	31.0
00 30	6.0	07 00	34.5	13 30	24.0	20 00	28.5
01 00	6.4	07 30	38.0	14 00	23.0	20 30	26.0
01 30	7.0	08 00	40.5	14 30	23.5	21 00	23.0
02 00	8.1	08 30	43.0	15 00	24.5	21 30	19.5
02 30	9.0	09 00	44.0	15 30	28.0	22 00	16.5
03 00	9.8	09 30	44.5	16 00	31.0	22 30	15.0
03 30	11.5	10 00	42.0	16 30	32.5	23 00	11.0
04 00	14.0	10 30	40.0	17 00	34.0	23 30	10.0
04 30	16.5	11 00	35.5	17 30	35.0	24 00	8.5
05 00	19.8	11 30	32.4	18 00	35.0	24 30	8.0
05 30	23.0	12 00	30.5	18 30	34.0	25 00	7.1
06 00	27.0	12 30	27.5	19 00	32.5	25 30	6.0

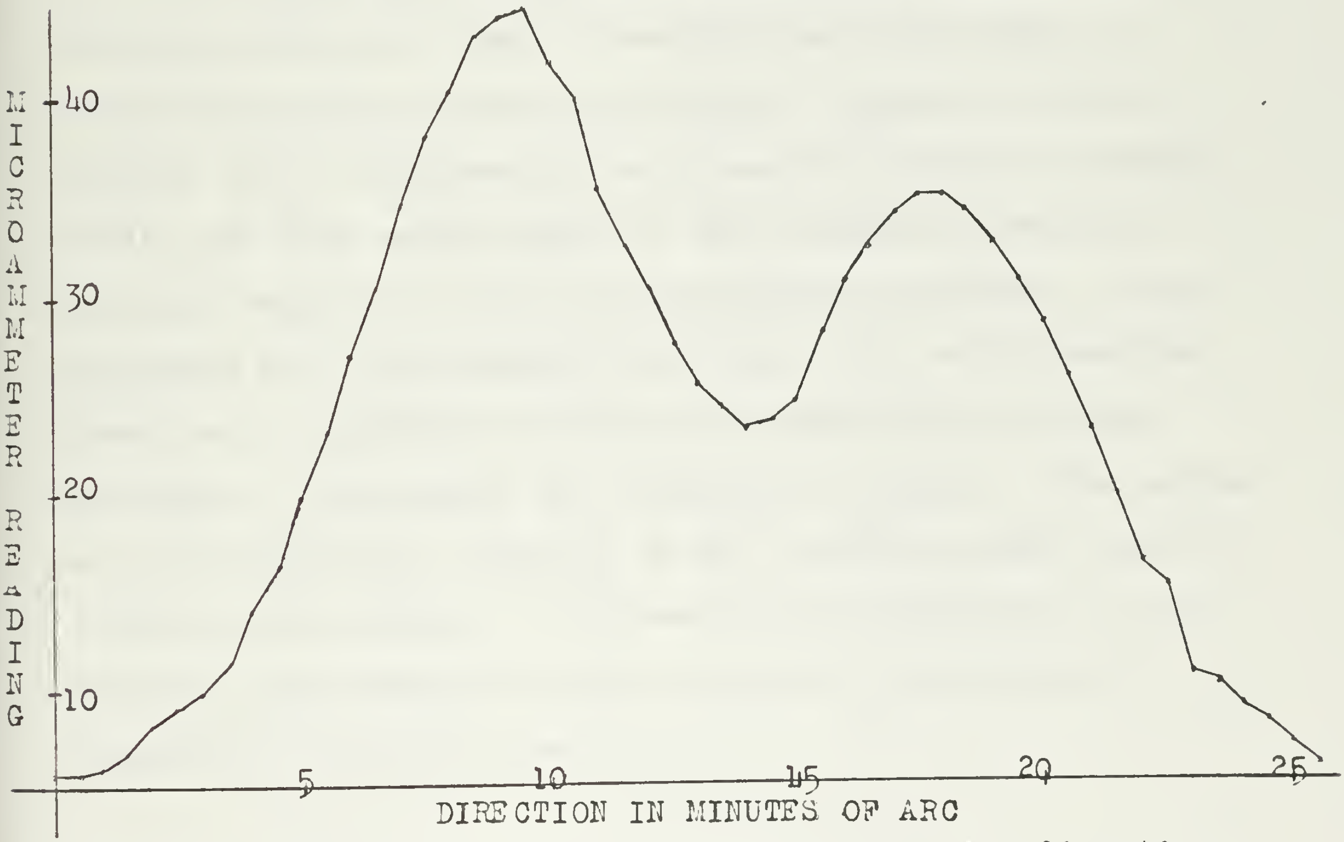

Fig. 4.2. Variation of microammeter reading with direction.

outlined by Cunningham will be subject to a systematic error, and is therefore not recommended. [2]

In this series of observations it was noted that the microammeter reading at each direction was not a constant with time as was expected. Naturally, an estimated mean reading was taken at each direction. All readings were taken moving the theodolite with the slow motion screw in the clockwise direction. Two questions now arise. First, is the variation of the microammeter with time such as to produce an error? Second, is any error introduced if readings are taken in the clockwise or counterclockwise direction?

To answer the two proceding questions another series of observations were made. Readings were again made in Denny Hall under the same conditions. A series of observations of the microammeter were made at various directions moving the slow motion screw in the clockwise direction, and then repeated in the counterclockwise direction. This procedure was then repeated four times. At each direction there was a variation of the microammeter and an average was taken. The results are tabulated in TABLE 3. The series of observations was repeated on the following night, and the results are in TABLE 4. The mean of the repetitions in the clockwise and counterclockwise directions are plotted as figures 4.3 and 4.4 respectively.

TABLE 3. - - Observations to determine if there is a difference between readings taken in the clockwise direction and readings taken in the counterclockwise direction.

All directions are in angular units of minutes and seconds.
The units of current are microamperes.

Direction	CW-CCW	Repetition 1	2	3	4	Mean
00' 00"	CW	1.8	2.0	2.0	2.0	2.0
	CCW	2.0	2.0	2.0	2.0	2.0
05' 00"	CW	2.0	2.0	2.0	2.0	2.0
	CCW	2.0	2.0	2.0	2.0	2.0
10' 00"	CW	2.0	2.0	2.0	2.0	2.0
	CCW	2.0	2.0	2.0	2.0	2.0
15' 00"	CW	7.0	9.0	10.0	8.0	8.5
	CCW	12.0	10.0	7.0	8.0	9.3
17' 30"	CW	15.0	12.0	11.0	12.0	12.5
	CCW	12.0	12.0	13.0	13.0	12.5
20' 00"	CW	32.0	32.0	29.0	30.0	30.8
	CCW	28.0	30.0	26.0	26.0	27.5
22' 30"	CW	24.0	20.0	20.0	22.0	21.5
	CCW	20.0	20.0	21.0	23.0	21.0
25' 00"	CW	26.0	28.0	23.0	28.0	26.3
	CCW	30.0	23.0	27.0	22.0	25.5
27' 30"	CW	22.0	20.0	20.0	21.0	20.8
	CCW	21.0	19.0	21.0	22.0	20.8
30' 00"	CW	19.0	19.0	15.0	16.0	17.3
	CCW	19.0	20.8	19.0	15.0	18.3
32' 30"	CW	5.0	5.0	6.0	6.0	5.5
	CCW	5.0	6.0	6.0	5.0	5.5
35' 00"	CW	3.0	2.2	2.0	2.0	2.3
	CCW	3.0	3.0	3.0	2.0	2.8
40' 00"	CW	2.0	2.0	2.0	2.0	2.0
	CCW	2.0	2.0	2.0	2.0	2.0

TABLE 4. - - Second series of observations to determine if there is a difference between readings taken in the clockwise direction and readings taken in the counterclockwise direction.

All directions are in angular units of minutes and seconds. The units of current are microamperes.

Direction	CW-CCW	Repetition 1	2	3	4	5	Mean
10' 00"	CW	10.5	9.0	8.2	8.0	7.2	8.6
	CCW	9.0	9.0	8.0	8.0	7.0	8.2
12' 00"	CW	17.5	14.0	13.2	13.0	11.2	13.8
	CCW	14.0	14.0	11.0	12.5	10.5	12.5
14' 00"	CW	30.5	22.5	20.2	20.8	17.0	22.2
	CCW	24.0	20.5	22.0	21.0	18.2	21.1
16' 00"	CW	37.0	28.5	25.5	23.8	24.8	27.9
	CCW	31.0	28.5	28.0	28.5	27.5	28.7
18' 00"	CW	31.0	28.0	26.0	24.0	26.5	27.1
	CCW	32.0	30.0	24.5	25.0	28.5	28.0
20' 00"	CW	30.0	31.0	28.8	27.0	26.0	28.6
	CCW	30.5	26.5	25.0	21.5	25.5	25.8
22' 00"	CW	37.5	36.0	32.6	31.2	29.2	33.3
	CCW	36.2	34.0	31.5	28.5	28.2	31.7
24' 00"	CW	37.5	31.5	27.0	29.2	28.1	30.7
	CCW	34.0	33.5	31.0	29.5	29.0	31.4
26' 00"	CW	27.0	24.5	22.0	22.8	20.5	23.4
	CCW	28.0	23.0	23.0	22.5	19.5	23.2
28' 00"	CW	19.0	16.0	14.5	13.5	14.5	15.5
	CCW	18.5	17.0	14.8	15.5	12.8	15.7
30' 00"	CW	12.0	10.0	10.5	9.0	9.0	10.1
	CCW	12.5	11.0	10.0	9.0	9.2	10.3

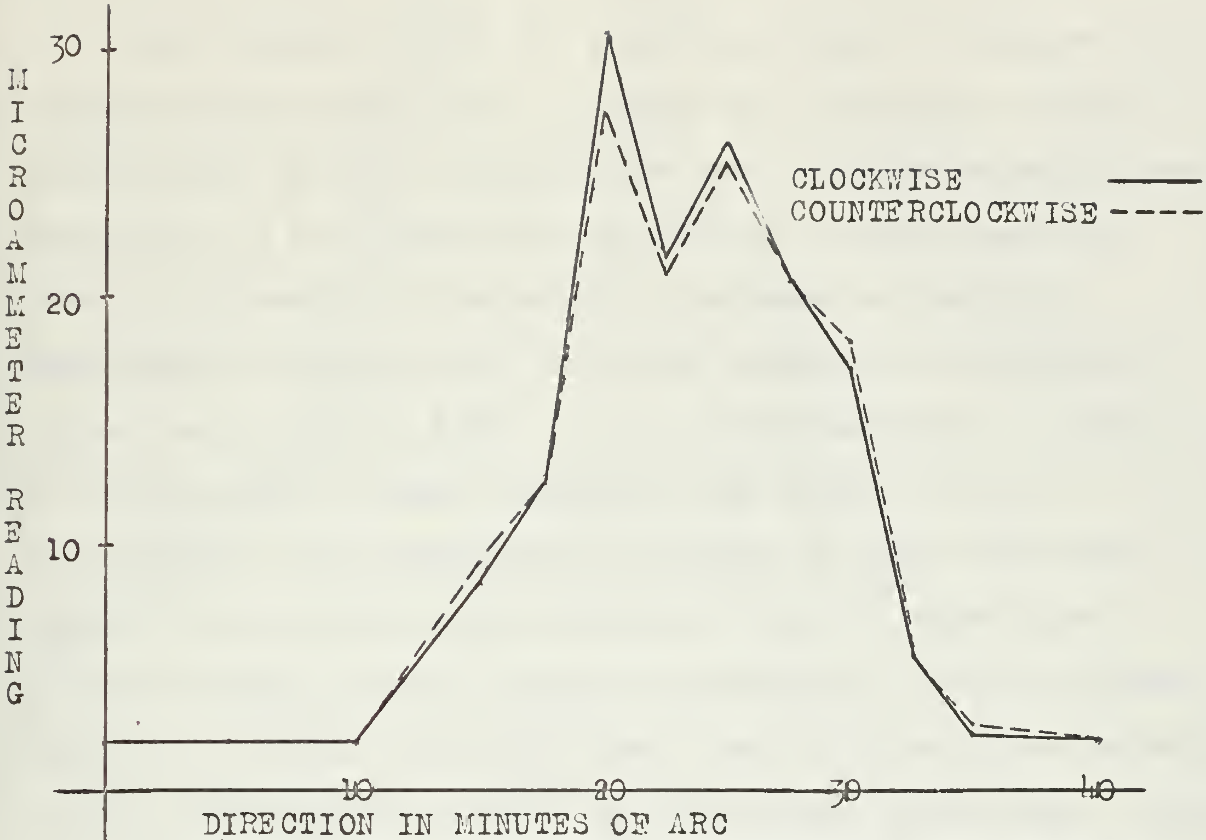

Fig. 4.3. Difference between the mean of clockwise and counterclockwise observations tabulated in Table 3.

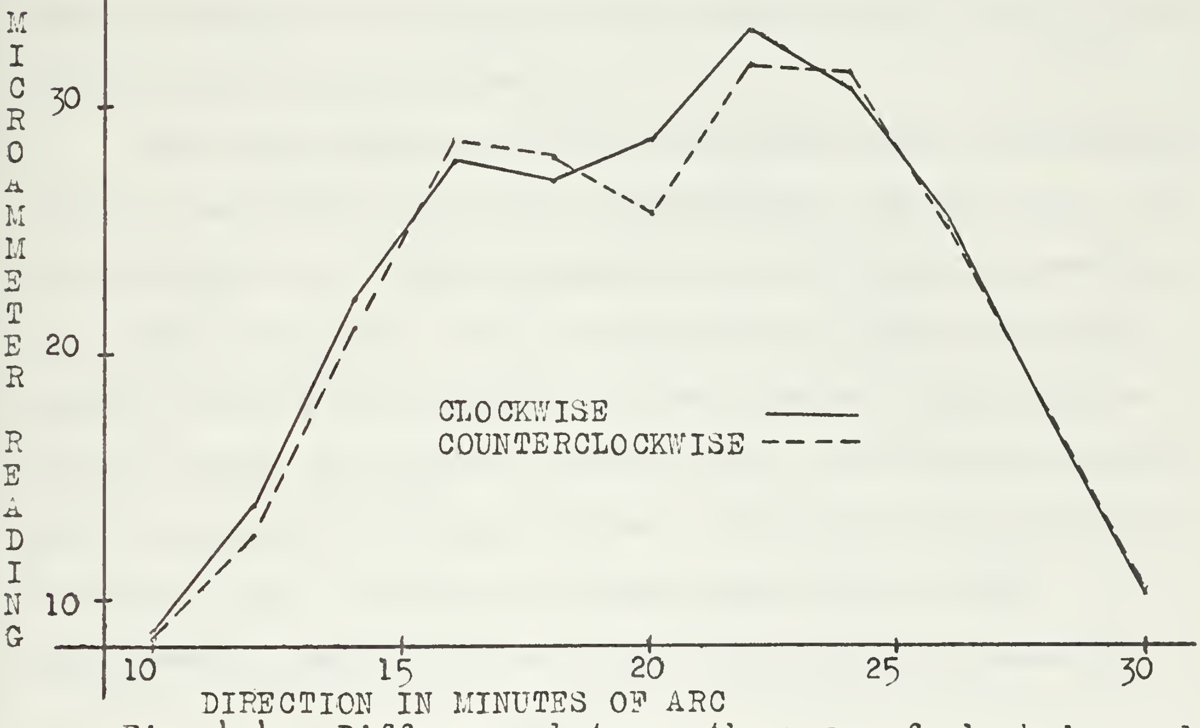

Fig. 4.4. Difference between the mean of clockwise and counterclockwise observations tabulated in Table 4.

The results of the two proceding series of observations indicate that there is not a systematic difference between observations made in the clockwise and counterclockwise direction. There also is no significant difference between readings made at increasing or decreasing microammeter readings. This indicates that there is no, or little, lost motion or system lag in the PM tube, or in the microammeter. A look at TABLES 3 and 4 shows, however, that there are wide variations in the microammeter readings at each direction. Figure 4.5 shows the curves described by the repetitions of observations in the clockwise direction. A look at these two sets of curves indicates that there is a definite variation of the microammeter readings at the various directions. There does not seem to be a variation in the shape of the laser beam, although the curves for the second night's observations do not show this too clearly.

The next series of observations were made to determine if this variation was in the microammeter, the PM tube, the laser output, or drastic changes in the propagating medium, ie., the atmosphere. The procedure was to read the microammeter every five seconds for five minutes. The microammeter reading was plotted against time, and then the points were connected by straight lines. The results are plotted as figure 4.6. In figure 4.6 the time scale and the microammeter scales are the same. The variable resistor

[illegible]

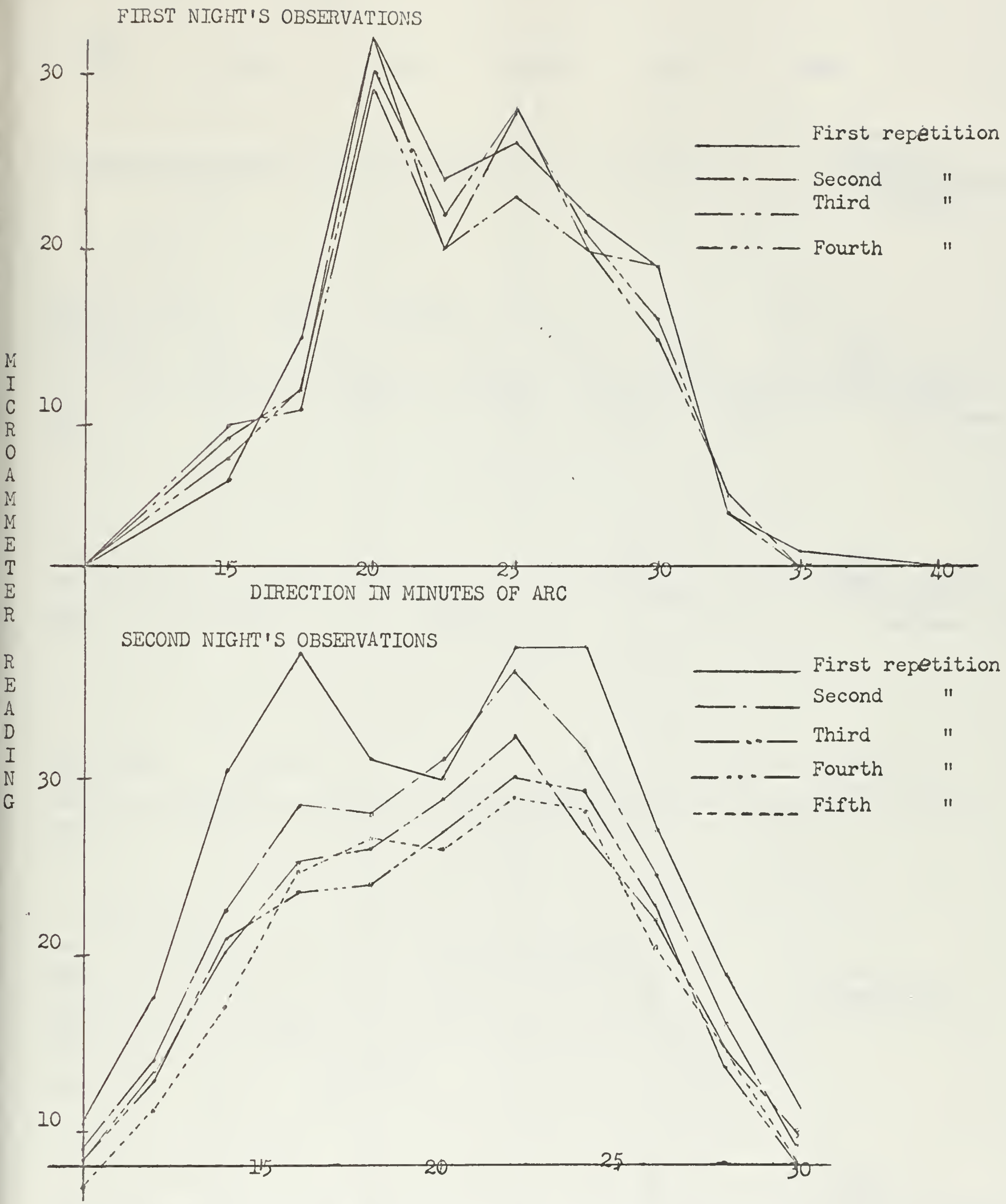

Fig. 4.5. Variation of microammeter readings with repetition.

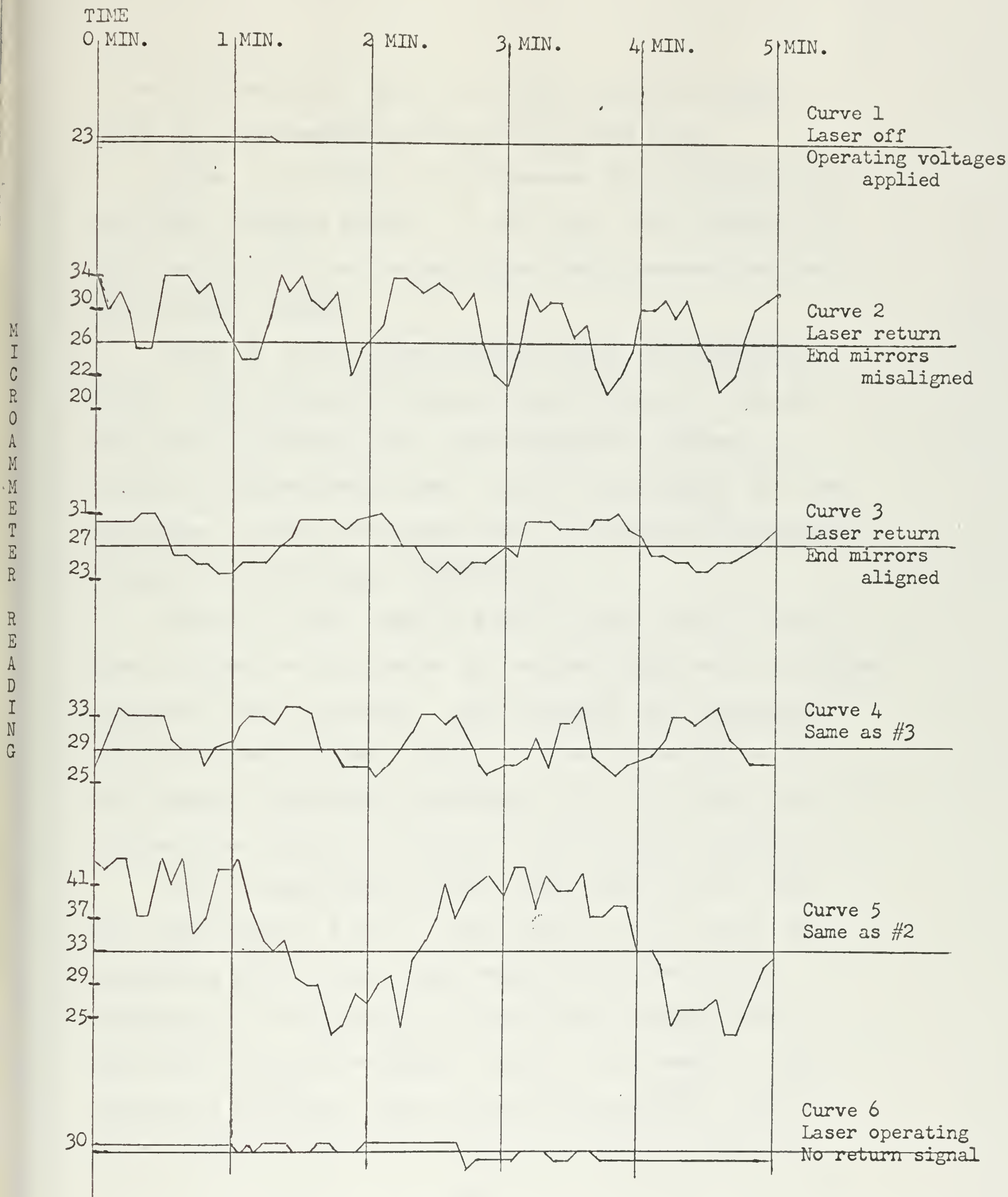

Fig. 4.6. Microammeter reading varying with time under various conditions.

across the output of the PM tube was adjusted to give about the same magnitude response in each case.

Curve 1 of figure 4.6 represents the condition with operating voltages applied to the laser, but without the laser lasing. It can be seen that the microammeter reading is quite steady.

Curve 2 is the laser return from a retrodirective mirror. The end mirrors were aligned in such a way that the laser was lasing, but were aligned to produce an ecliptic, non-maximum, beam. Curve 5 represents the same condition. These two curves show the maximum fluctuations of any of the operating conditions.

Curve 3 is the same as 2 and 5, but with the laser beam as close to maximum as the author could make it without elaborate test equipment. The alignment was destroyed, and then brought back. Curve 4 is the second curve of near maximum operating conditions. It can be seen that the fluctuations are still present, but of lesser magnitude.

Curve 6 was made with the laser operating in the same condition as 3 and 4, but with the dust covers on, preventing most of the laser output from leaving the instrument. Furthermore, the laser was directed away from any reflective surface. Curve 6 represents steady background light but with the laser operating. Curve 6 has fluctuations that are absent from Curve 1, but are

small in magnitude.

Curve 6 indicates that the fluctuations are, to some extent related to the mere fact of the laser operating. Since the magnitudes of curves 2 through 5 are considerably larger than curve 6 this is not the main reason. Since the magnitude of curves 2 and 5 are larger than curves 3 and 4, we can also say that the fluctuations are also dependent on the alignment of the end mirrors. The variations present in curves 3 and 4 are considerable, and need further explanation.

In order to determine the cause of these variations, the equipment was taken to the Antenna Laboratory, Ohio State Research Center, and the expert opinion of Mr. William Swarner was obtained. With the more elaborate test equipment available at the Research Center it was determined that the fluctuations were present in the laser output itself. It was also found that the DC-DC converter supplying the laser, even though it is unregulated, supplied a voltage that was steady to one volt (less than a 0.3% variation), and the current in the plasma tubes was steady. The equipment had operated for at least thirty minutes and thermal equilibrium must have been reached. At the same time the laser output was fed to an independent test instrument, and the same power variations were observed. In view of the small variations that were observed in the plate voltage it seems unlikely that a regulated converter would eliminate this problem

completely, but it may well be worth the expense. This is a problem to be more fully analysed by an electronics engineer.

Mr. Swarner's opinion was that the variations were due to changing conditions within the plasma tubes of the laser itself. This may have been due to the glass walls of the plasma tubes not being perfectly clean, the vacuum in the tubes may not have completely held, or some of the active gases may have been absorbed by the glass walls. It is more probable that it is the result of the summation of a number of causes. According to Mr. Swarner this type of phenomenon has been noted at the Antenna Laboratory, but there is no definative data available. However, again according to Mr. Swarner, the variations in this particular laser seem to be larger than those observed at the Antenna Laboratory. In his opinion this laser has almost reached the end of its useful life.

At this point the laser became inoperable for about five days. The problem was that the laser, over a period of about two hours, gradually became dim, and finally went out. When this happened before it was usually that the battery needed recharging or the end mirrors had gone out of alignment. Neither one of these causes proved to be the cause of the problem. After cleaning the optics I took the laser again to the Antenna Laboratory. Mr. Frank Jacoby

was able to correct the problem, which proved to be that the Brewster Windows were dirty. This incident is of interest because the author had cleaned the optics not more than a few hours before. This is indicative that more than just casual care must be given to the internal optics of a laser to obtain even partial operation of the system.

The next series of observations were made to determine if the laser beam shape changes with changes in alignment of the end mirrors. A series of observations were made in Denny Hall deliberatly changing the alignment four times. The results of these observations are tabulated in TABLE 5 and the various curves described are shown in figure 4.7. The results are, briefly, that the laser beam is seriously deformed by changes in alignment, except that the direction of maximum response remains the same (to the limits of the interval between observations).

Figure 4.7, taken in conjunction with figure 4.5, presents problems. The alignment of the laser was not changed by the operator during the observations that described figure 4.5. However, there may have been some change in the alignment beyond the control of the operator that caused the result apparent in figure 4.5. More likely is that there is a combination of effects, such as changing alignment and possible absorption of the active gases by the glass walls of the plasma tubes. Also notable in TABLE 5 is that the

TABLE 5. - - Observations made to determine if the shape of the laser beam varies significantly with the alignment of the end mirrors.

Alignment One

Dir.	CW	CCW	CW	CCW
00	10	8	9	7
02	20	17	18	16
04	35	31	32	31
06	41	37	38	41
08	36	34	36	37
10	32	31	30	35
12	29	30	32	35
14	26	27	27	28
16	17	18	14	14
18	8	9	7	7
20	4	4	4	4

Alignment Two

Dir.	CW	CCW	CW	CCW
00	3	3	3	3
02	7	6	6	5
04	17	15	16	14
06	25	23	22	22
08	20	19	18	18
10	14	13	13	10
12	15	14	14	14
14	19	18	15	15
16	12	12	11	11
18	6	6	6	6
20	3	3	3	3

Alignment Three

Dir.	CW	CCW	CW	CCW
00	3	3	2	2
02	5	5	6	5
04	13	11	12	12
06	19	18	19	18
08	16	15	16	14
10	12	11	11	9
12	11	10	9	9
14	13	12	13	13
16	10	10	11	10
18	5	6	5	5
20	2	2	2	2

Alignment Four

Dir.	CW	CCW	CW	CCW
00	3	3	3	3
02	10	9	9	8
04	25	21	23	24
06	42	41	40	39
08	35	35	34	34
10	19	21	18	20
12	20	19	19	18
14	25	26	25	26
16	21	22	21	21
18	10	10	9	10
20	3	4	3	4

Mean Values

Dir.	One	Two	Three	Four
00	8.5	3.0	2.5	3.0
02	17.8	6.0	5.3	9.0
04	32.3	15.5	12.0	23.3
06	39.3	23.0	18.5	40.5
08	35.8	18.8	15.3	34.5
10	32.0	12.5	10.8	19.5
12	31.5	14.3	9.8	19.0
14	27.0	16.8	12.8	25.5
16	15.8	11.5	10.3	21.5
18	7.8	6.0	5.3	9.8
20	4.0	3.0	2.0	3.5

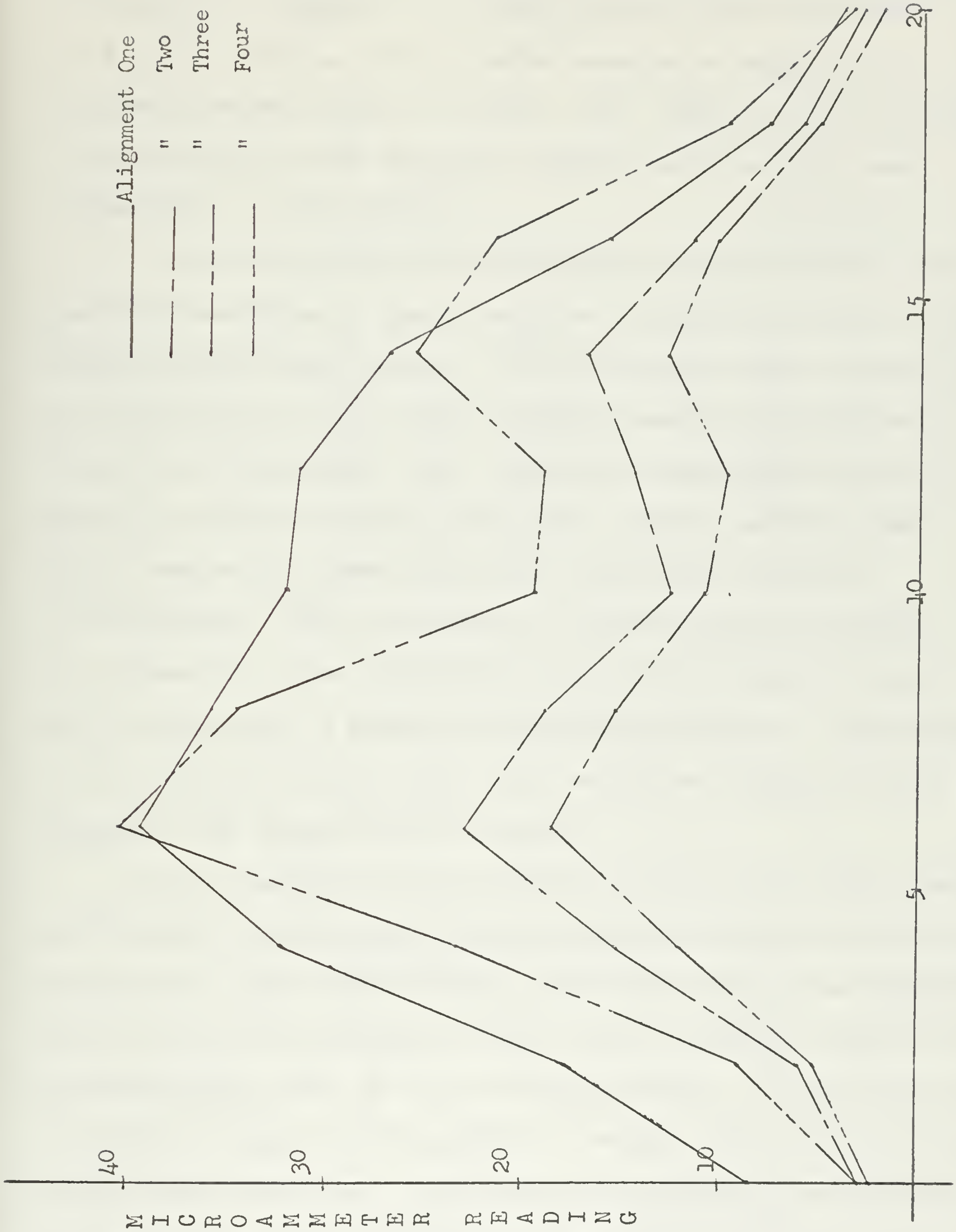

Fig. 4.7. Variation of microammeter readings versus direction for various alignments of the laser end mirrors.

variations so apparent in TABLES 3 and 4 have diminished to a great extent, and no longer seem to be dependent on alignment as was noted in figure 4.6. This is due to the fact that the dirt on the Brewster Windows must have put some instability in the system.

The final series of observations in this section were made to determine if there would be a source of error if the target mirror were rotated. It is obvious that if there is a translation of the target an error would be introduced. TABLE 6 is the results of a series of observations made with a rotation of about forty five degrees between the first series of observations and the second series of observations. The two series of observations are plotted in figure 4.8. The discrepancy that can be seen in figure 4.8 is small for a change of forty five degrees. The changes in the mirrors in the field will be of the order of a few degrees, and should be no problem.

As a summary of this section it can be said that there are two main sources of error in the laser section of the laser theodolite. The first is that tha laser beam is not symmetrical. This error can be avoided in the field if care is taken to compare corresponding parts of the returning signal. The second cause of error is that the microammeter reading will vary from causes other than direction. This cause of error will be minimized by taking the mean of a number of observations.

TABLE 6. - - Observations taken to determine if the returning signal from a retrodirective mirror depends on the alignment of the mirror relative to the laser.

Between observations I and II the target mirror was rotated about forty five degrees.

Direction	Observation I Repetition 1	Observation I Repetition 2	Observation I Mean	Observation II Repetition 1	Observation II Repetition 2	Observation II Mean
00' 00"	4	4	4.0	5	5	5.0
02 00	8	7	7.5	10	10	10.0
04 00	15	14	14.5	19	18	18.5
06 00	22	21	21.5	24	24	24.0
08 00	25	24	24.5	27	26	26.5
10 00	29	28	28.5	32	31	31.5
12 00	33	32	32.5	34	35	34.5
14 00	31	32	31.5	30	32	31.0
16 00	23	23	23.0	19	20	19.5
18 00	11	12	11.5	9	10	9.5
20 00	5	6	5.5	4	4	4.0

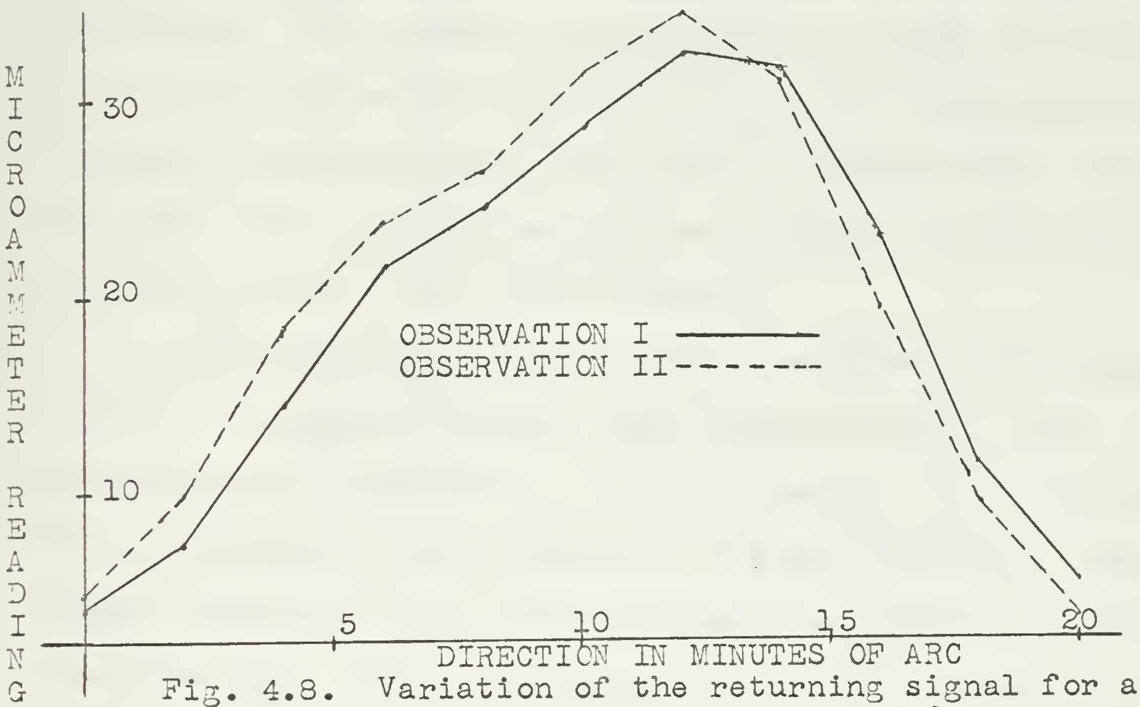

Fig. 4.8. Variation of the returning signal for a change of target alignment of about 45 degrees.

4.3. THE MEASUREMENT OF HORIZONTAL ANGLES

Having made an investigation of the sources of errors in the laser theodolite the next step was to measure a horizontal angle to see if the results were as expected. Two requirements forced me to make these measurements indoors in Denny Hall. The first limitation was that I was unable to keep the instrument in a stable state out of doors during earlier attempts. This was due to changing weather conditions that had injurious effects on the laser. The second reason was that the instrument's filter was of the wrong peak pass wavelength. Therefore, the instrument could only be used without any filter, necessitating a dark location. On April 21, 1966, I made a series of observations in room 6 of Denny Hall, setting two retrodirective mirrors at a distance of 6.4 meters from the theodolite. The results are tabulated in TABLE 7. During the series of observations the shutter on the PM tube, and the variable resister across the output of the PM tube, were not changed. The variable resister was adjusted prior to the observations to give a near peak response.

The results are about what was expected. The standard error of the mean of thirty four observations is only $\pm 2\overset{''}{.}1$ which must be considered to be high quality. At 6.4 meters $2\overset{''}{.}1$ represents a linear distance of about 0.006 cm. This is a higher precision than I could measure the center of a mirror from one edge. There are sources of error outlined in section

TABLE 7. - - Observations taken in room 6 of Denny Hall on 21 Apr 1966.

	Left			Right			Mean			v
				Readings at 20 μamps.						
Target 1	254°	35'	37".5	254°	52'	08".4	254°	43'	53".0	
		35	22.7		52	24.3		43	53.5	
		35	24.6		52	25.0		43	54.8	
		35	18.9		52	33.9		43	56.4	
		35	11.8		52	36.4		43	54.1	
		35	15.4		52	30.7		43	53.1	
Mean	254	35	21.8	254	52	26.5	254	43	54.2	
Target 2	251	28	26.3	251	45	27.5	251	36	56.9	
		28	28.7		45	48.8		37	08.8	
		28	25.8		45	43.0		37	04.4	
		28	26.3		45	43.2		37	04.8	
		28	18.1		45	55.7		37	06.9	
		28	18.2		45	46.8		37	02.5	
Mean	251	28	23.9	251	45	44.2	251	37	04.1	
Angle	3	07	11.2	3	06	40.9	3	06	56.1	6.0
		06	54.0		06	35.5		06	44.7	-5.4
		06	58.8		06	42.0		06	50.4	0.3
		06	52.6		06	50.7		06	51.6	1.5
		06	53.7		06	40.7		06	47.2	-2.9
		06	57.2		06	43.9		06	50.6	0.5
Mean	3	06	57.9	3	06	42.3	3	06	50.1	

[vv] = 76.16　　[vv] /n-1 = 15.23　　m = ± 3".9

	Left			Right			Mean		
				Readings at 25 μamps.					
Target 1	254	37	10.7	254	51	06.7	254	44	08.7
		37	01.3		51	09.9		44	05.2
		37	05.7		51	08.9		44	07.3
		37	00.8		51	10.8		44	05.8
		37	08.8		51	03.7		44	06.3
		37	07.3		51	03.5		44	05.4
Mean	254	37	05.8	254	51	07.1	254	44	06.4

TABLE 7. - - Continued

Target 2	251°	30'	11".7	251°	44'	13".2	251°	37'	12".5	
		30	06.0		44	26.3		37	16.2	
		30	03.9		44	23.0		37	13.4	
		30	00.8		44	28.6		37	14.7	
		30	06.5		44	16.8		37	11.7	
		30	09.3		44	26.2		37	17.7	
Mean	251	30	06.4	251	44	22.4	251	37	14.4	
Angle	3	06	59.0	3	06	53.5	3	06	56.2	4.1
		06	55.3		06	42.7		06	49.0	-3.1
		07	01.8		06	45.9		06	53.9	1.8
		07	00.0		06	42.2		06	51.1	-1.0
		07	02.3		06	46.9		06	54.6	2.5
		06	58.0		06	37.3		06	47.7	-4.4
Mean	3	06	59.4	3	06	44.7	3	06	52.1	

[vv] = 56.27 [vv] /n-1 = 11.254 m = ± 3".6

Reading at 30 μamps.

Target 1	254	38	11.0	254	49	44.1	254	43	57.6
		38	11.0		49	45.8		43	58.4
		38	05.8		49	40.7		43	53.3
		38	32.6		49	43.3		44	08.0
		38	12.2		49	38.1		43	55.2
		38	33.3		49	42.0		44	07.6
Mean	254	38	17.7	254	49	42.3	254	44	00.0

Target 2	251	31	21.4	251	43	12.8	251	37	17.1	
		31	32.5		43	08.8		37	20.7	
		31	25.5		43	00.7		37	13.1	
		31	38.7		43	06.3		37	22.5	
		31	14.2		43	04.7		37	09.5	
		31	28.9		43	06.9		37	17.9	
Mean	251	31	26.9	251	43	06.7	251	37	16.8	
Angle	3	06	49.6	3	06	31.3	3	06	40.5	-2.7
		06	38.5		06	37.0		06	37.7	-5.5
		06	40.3		06	40.0		06	40.2	-3.0
		06	53.9		06	37.0		06	45.5	2.3
		06	58.0		06	33.4		06	45.8	2.6
		07	04.4		06	35.1		06	49.7	6.5
Mean	3	06	50.8	3	06	35.6	3	06	43.2	

[vv] = 100.84 [vv] /n-1 = 20.17 m = ± 4".5

Reading at 35 μamps.

Target 1	254°	40'	02".5	254°	48'	57".4	254°	44'	30".0	
		40	39.7		48	51.8		44	45.7	
		41	09.0		48	56.5		45	02.8	
		42	13.5		48	48.9		45	31.2	
		41	16.9		49	04.8		45	10.9	
		41	02.2		48	53.3		44	57.7	
Mean	254	41	04.0	254	48	55.4	254	44	59.7	
Target 2	251	32	40.3	251	42	27.6	251	37	34.0	
		33	22.2		42	15.0		37	48.6	
		34	08.7		42	12.9		38	10.8	
		33	44.3		42	09.1		37	56.7	
		33	58.5		42	31.0		38	14.8	
		33	49.1		42	25.5		38	07.3	
Mean	251	33	37.2	251	42	20.2	251	37	58.7	
Angle	3	07	22.2	3	06	29.8	3	06	56.0	-5.0
		07	17.5		06	36.8		06	57.1	-3.9
		07	00.3		06	43.6		06	52.0	-9.0
		08	29.2		06	39.8		07	34.5	33.5
		07	18.4		06	33.8		06	56.1	-4.9
		07	13.1		06	27.8		06	50.4	-10.6
Mean	3	07	26.8	3	06	35.3	3	07	01.0	

$[vv] = 1379.83$ $[vv]/n-1 = 276.0$ $m = \pm 16''.5$

Since the residual 33.5 is more than twice the standard error, and the other five residuals have the opposite sign, I will reject that observation. The new mean value of the angle is 3° 06' 54".3 and the standard error of a single observation is ±2".9

Reading at 40 μamps.

Target 1	254	42	39.1	254	47	11.1	254	44	55.1
		42	43.4		47	12.2		44	57.8
		42	34.5		47	57.1		45	15.8
		42	43.2		47	59.0		45	21.1
		43	08.6		48	17.5		45	43.1
		43	05.1		48	09.4		45	37.3
Mean	254	42	49.0	254	47	47.7	254	45	18.4
Target 2	251	35	58.2	251	40	42.0	251	38	20.1
		36	07.0		41	03.7		38	35.4
		35	21.7		41	09.6		38	15.7
		35	08.2		41	37.1		38	22.6
		35	28.2		41	49.4		38	38.8
		35	53.5		41	50.4		38	52.0
Mean	251	35	39.5	251	41	22.0	251	38	30.8

TABLE 7. - - Continued

Angle	3° 06' 40".9	3° 06' 29".1	3° 06' 35".0	-12.6
	06 36.4	06 08.5	06 22.4	-25.2
	07 12.8	06 47.5	07 00.1	12.5
	07 35.0	06 21.9	06 58.4	10.8
	07 40.4	06 28.1	07 04.3	16.7
	07 11.6	06 19.0	06 45.3	-2.3
Mean	3 07 09.7	3 06 25.7	3 06 47.6	

[vv] = 1192.11   [vv] /n-1 = 238.42   m = ±15".3

Reading at peak current

Target 1 I	Target 1 Direction	Target 2 I	Target 2 Direction	Angle	v
42	254° 45' 41".6	48	251° 39' 22".0	3° 06' 19".6	-22.6
44	46 10.4	49	39 09.7	07 00.7	18.5
42	45 56.5	46	39 21.7	06 34.8	-7.4
43	46 44.9	48	39 27.3	07 17.6	35.4
43	46 14.2	48	39 56.0	06 18.2	-24.0
	254 46 09.5		251 39 27.3	3 06 42.2	

[vv] = 2736.93   [vv] /n-1 = 684.2   m = ±26".1

Summary

The mean angle of the 34 observations is	3° 06' 48".3
The standard error of a single observation is	12.4
The standard error of the mean of 34 observations is	2.1

To show a possible systematic error that can be introduced if care is not taken to avoid it:

Current μamps	Target 1 Mean	Target 2 Mean	Angle Mean	m
15		Background Level		
20	254 43 54.2	251 37 04.1	3 06 50.1	±3.9
25	44 06.4	37 14.4	06 52.1	±3.6
30	44 00.0	37 16.8	06 43.2	±4.5
35	44 59.7	37 58.7	06 54.3	±2.9
40	45 18.4	38 30.8	06 47.6	±15.3
Peak	46 09.5	39 27.3	06 42.2	±26.1

Were the mean direction to the target mirrors taken at different values of microammeter reading an error, in this case, with a magnitude in minutes of arc would be introduced.

4.1. that would be rectified in a production model laser theodolite. Therefore, I did not attempt to determine the exact angle by means of measuring the sides of the triangle formed by the two mirrors and the theodolite.

The standard error of the observations made at the peak value are much worse than those at other microammeter readings. This is from the fact that there is no real peak value of the curve of the microammeter reading varying with direction, but rather a plateau like curve. This makes the determination of the direction of the peak reading quite difficult.

The standard error of the readings at 40μamps. is also worse than readings at lesser values of the microammeter readings. Figure 4,9 is the curves of the microammeter reading varying with direction for each target. It can be seen that the slope of these curves is decreasing at 40μamps. and is more or less constant at lesser values of microammeter readings. It can also be seen that the standard error seems to be a more or less constant below 40μamps. As a conclusion it can be said that the most accurate angular measurements will be made at the greatest slope of the curve of microammeter reading varying with direction, and that this slope is nearly constant to nearly peak response.

One source of error could be the changing of alignment of the end mirrors as can be seen in TABLE 5 and figure 4-7.

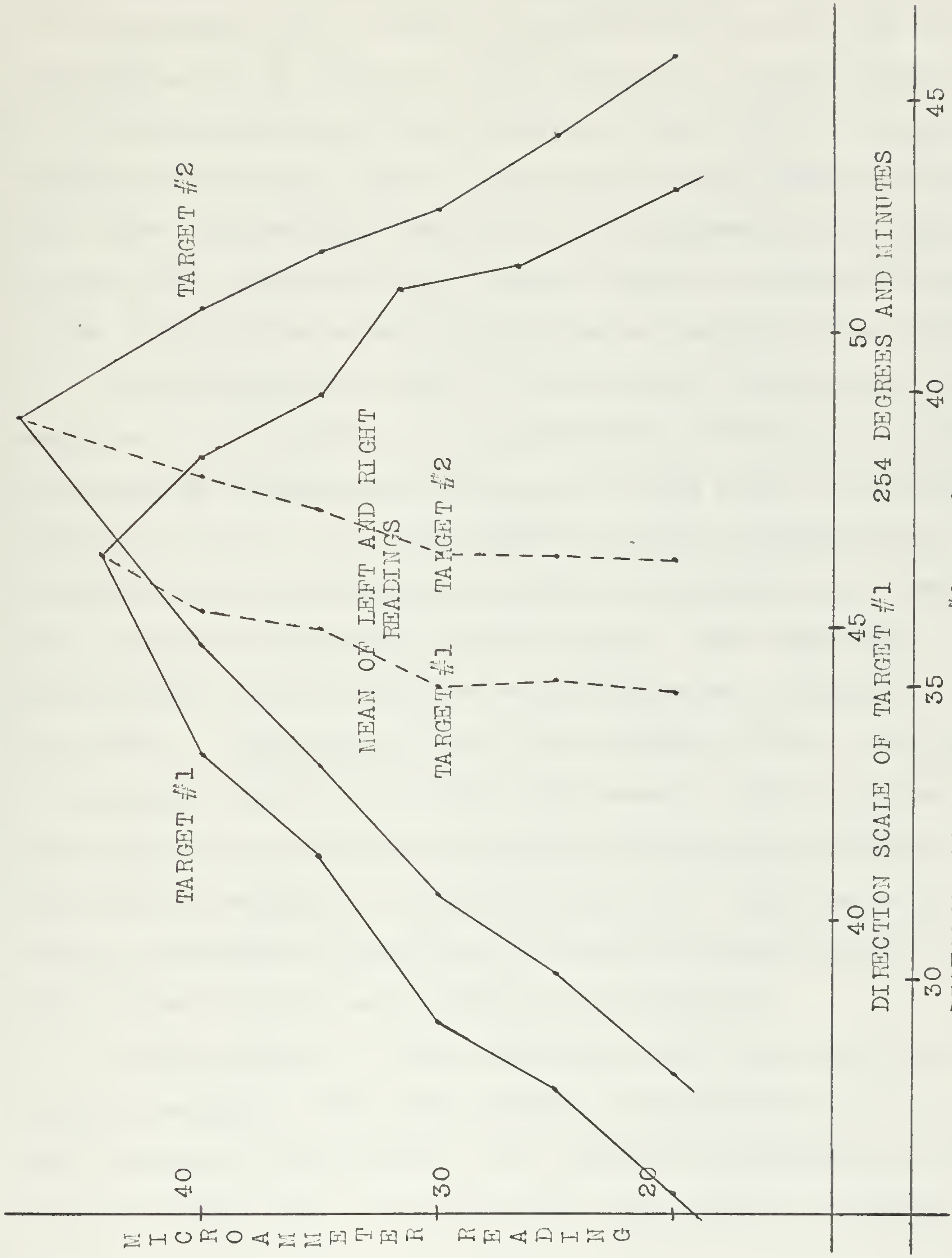

Fig. 4.9. Observations of a horizontal angle tabulated in TABLE 7.

There is no indication that this happened during this series of observations. One reason for saying this is that only one observation out of thirty five was rejected. Another reason is the small magnitude of the standard errors and the marked relation between the slope of the curve and the standard error. Were there considerable changing of the alignment of the end mirrors there would be more a random relation of standard error to the slope of the curve of microammeter reading versus direction.

There remains one error of considerable importance. The response of the mirrors is not symmetrical. This can be avoided by comparing corresponding midpoints of each curve. Were this not done, that is, if we determined an angle by subtracting the directions to midpoints that did not correspond, an error with a magnitude of minutes would result. What would make matters worse would be that we would determine a standard error with a magnitude of only a few seconds of arc. Care must be taken that this is not done. The laser in the Cunningham Laser Theodolite does not have collimating lenses and has a rated beam divergence of thirty arc minutes. Were the laser output collimated we would have a much more narrow output, but this source of error would still be considerable.

To be more sure of the conclusions this procedure was repeated on May 5, 1966, with Captain William Sprinsky, U. S. Army, acting as the observer. The results are tabulated in TABLE 8 and in figure 4-10. This time the target was at a distance

TABLE 8. - - Observations taken in room 6 of Denny Hall on 5 May 1966.

	Target 1	Target 2	Angle	v
	Readings at 20 μamps.			
Right	280° 51' 28".9	275° 23' 26".8	5° 28' 02".1	
Left	35 55.0	09 37.3	26 17.7	
Mean			27 09.9	11.05
	51 26.2	23 44.7	27 41.5	
	35 59.6	09 44.3	26 15.3	
			26 58.4	-.45
	51 32.9	23 51.4	27 41.5	
	35 55.0	09 36.5	26 18.5	
			27 00.0	1.15
	51 33.4	24 01.0	27 32.4	
	36 01.5	09 47.1	26 14.4	
			26 53.4	-5.45
	51 40.5	23 49.2	27 51.3	
	35 46.0	09 48.8	25 57.2	
			26 54.3	-4.55
	51 41.7	24 00.7	27 41.0	
	36 11.6	09 58.3	26 13.3	
			26 57.1	-1.75
[vv] = 177.095		[vv] /n-1 = 35.42	m = ±6".0	
	Readings at 25 μamps.			
Right	280° 47' 20".1	275° 19' 13".4	5° 28' 06".7	
Left	37 25.1	11 24.3	26 00.8	
Mean			27 03.7	-.6
	44 07.3	31 07.7	12 53.6	
	37 17.7	11 33.3	26 44.4	
			19 49.0	REJECTED
	47 52.7	19 23.1	28 29.6	
	37 22.4	11 06.8	26 15.6	
			27 22.6	18.3
	47 32.9	19 31.4	28 01.5	
	37 32.6	11 37.7	25 54.9	
			26 58.2	-6.1
	46 36.0	19 08.6	27 27.4	
	37 37.0	11 42.5	25 54.5	
			26 41.0	-23.3
	47 25.0	19 07.0	28 18.0	
	37 33.4	11 37.2	25 56.2	
			27 07.1	2.8

		47	37.3		19	24.7		28	12.6	
		37	46.1		11	32.2		26	13.9	
								27	13.2	8.9

[vv] = 1002.4 [vv] /n-1 = 200.48 m = ±14".2

Readings at 30 µamps.

Right	280°	45'	49".2	275°	18'	05.7	5°	27'	43".5	
Left		38	36.2		12	43.5		25	52.7	
Mean								26	48.1	4.9
		45	52.3		18	14.7		27	37.6	
		38	30.1		12	45.0		25	45.1	
								26	41.4	-1.8
		45	40.3		18	11.1		27	29.2	
		38	13.5		12	41.3		25	32.2	
								26	30.7	-12.3
		45	49.5		18	05.1		27	44.4	
		38	18.6		12	33.9		25	44.7	
								26	44.5	1.3
		45	54.2		18	02.6		27	51.6	
		38	26.3		12	39.0		25	47.3	
								26	49.5	6.3
		45	46.8		18	01.7		27	45.1	
		38	30.3		12	45.4		25	44.9	
								26	45.0	1.8

[vv] = 223.16 [vv] /n-1 = 44.63 m = ±6".7

Readings at 35 µamps.

Right	280°	45'	24".8	275°	17'	45".2	5°	27'	39".6	
Left		38	40.7		12	35.9		26	04.8	
Mean								26	52.2	13.95
		45	23.0		17	53.3		27	29.7	
		38	25.5		12	48.8		25	36.7	
								26	33.2	-5.05
		45	25.6		17	49.3		27	36.3	
		38	14.6		12	33.3		25	41.3	
								26	38.8	.55
		45	23.1		17	52.8		27	30.3	
		38	52.6		13	04.4		25	48.2	
								26	39.2	.95
		45	23.9		17	46.7		27	37.2	
		38	41.1		13	02.3		25	38.8	
								26	38.0	-.25

	45 32.7	17 46.5	27 46.2	
	38 25.1	13 15.1	25 10.0	
			26 28.1	-10.15

[vv] = 324.395 [vv] /n-1 = 64.879 m = ± 8".0

Readings at 40 μamps.

Right	280° 44' 27".8	275° 16' 39".4	5° 27' 48".4	
Left	40 06.2	14 34.2	25 32.0	
Mean			26 40.2	-5.5
	44 26.7	16 04.1	28 22.6	
	39 58.4	15 22.9	24 35.5	
			26 29.1	-16.6
	44 17.8	15 30.6	28 47.2	
	40 35.5	15 01.3	25 34.2	
			27 10.7	25.0
	44 20.2	15 59.3	28 20.9	
	40 41.0	15 36.5	25 04.5	
			26 42.7	-3.0

[vv] = 939.81 [vv] /n-1 = 313.27 m = ±17".7

Readings at peak current

Target 1	Target 2	Angle	v
280° 46' 53".8	275° 19' 54".0	5° 26' 59".8	8.5
47 00.2	20 19.3	26 40.9	-10.4
46 47.5	19 50.2	26 57.3	6.0
46 33.3	20 03.1	26 30.2	-20.1
46 32.3	19 38.0	26 54.3	3.0
46 03.2	20 31.1	25 32.1	-79.2
46 02.2	19 23.7	26 38.5	-12.8
46 37.7	20 08.7	26 29.0	-22.3
47 34.0	19 44.6	27 49.4	58.1
47 23.6	19 41.1	27 42.5	51.2
47 50.4	19 42.3	28 08.1	76.8
46 27.3	20 02.3	26 25.0	-28.1
46 40.7	19 03.9	27 36.8	45.5
46 45.7	20 49.1	25 56.6	-54.7
47 16.6	20 46.0	26 30.6	-20.7
47 25.5	20 35.3	26 50.2	-1.1

[vv] = 25,740.13 [vv] /n-1 = 1716.01 m = ± 41"

Summary

The readings other than those at peak value were made by Captain William Sprinsky, U. S. Army. For his observations the following angles were determined:

5° 27'	19".9	19".53
26	58.4	8.03
27	00.0	9.63
26	53.4	3.03
26	54.3	3.93
26	57.1	6.73
27	13.7	13.33
27	22.6	32.23
26	58.2	7.83
26	41.0	-9.37
27	07.1	16.73
27	13.2	22.83
26	48.1	-2.27
26	41.4	-8.97
26	30.7	-19.67
26	44.5	-5.87
26	49.5	-.87
26	45.0	-5.37
26	52.2	1.83
26	33.2	-17.17
26	38.8	-11.57
26	39.2	-11.17
26	38.0	-12.37
26	28.1	-22.27
26	40.2	-10.17
26	29.1	-21.27
27	10.7	20.33
26	42.7	-7.67

The mean angle of the 28 observations 5 26' 50".37
The standard error of a single observation is ± 14.3
The standard error of the mean of the 28 observations is ± 2.7

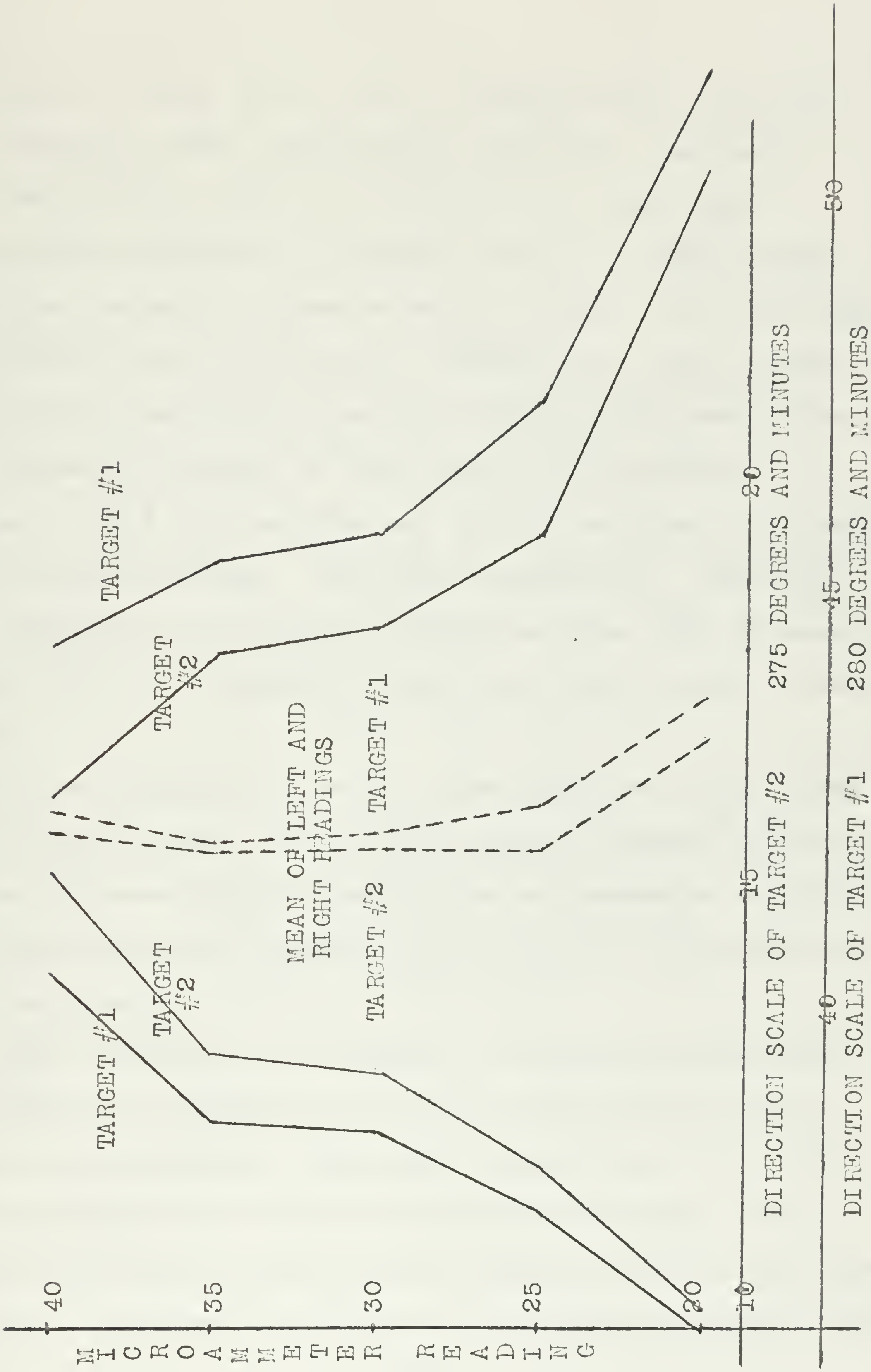

Fig. 4.10. Observations of a horizontal angle tabulated in TABLE 8.

of 5.7 meters. During this series of observations the micro-ammeter readings showed considerable variations, much more than in the previous series of observations. Only four repetitions were possible at 40 μamps. when, for some reason, the response from target #2 decreased below 40 μamps. At this time Captain Sprinsky was called away. Thinking that the vertical lock may have slipped and that we were no longer in the same plane, the author changed the setting of the laser in the vertical attempting to find some position at which a response from target #2 was more than 40 μamps. This was unseccessful. Therefore, sixteen readings at peak current (which was less than 40 μamps. from target #2) in an arbitrary position related to the vertical were made.

In other respects the results were similiar to the first series of observations. The slightly larger standard errors are due to the increased fluctuations in the microammeter readings. It is believed that the standard error of $\pm 14\overset{''}{.}2$ at 25 μamps. is a random occurrence.

Of more interest is the change of direction between the mean of Sprinsky's readings, and the direction of peak power as measured by the author. The angle measured is $5° \ 26' \ 50\overset{''}{.}37$ $\pm 2\overset{''}{.}7$ for Sprinsky and $5° \ 26' \ 51\overset{''}{.}3 \ \pm 10\overset{''}{.}$ for the author. The agreement of the angle shows that the mirrors and the theodolite did not move. However, the individual directions disagree with a

magnitude in minutes of arc. The initial explanation of this was that the laser beam, along with not being symmetrical in the horixontal sense, was not symmetrical in the vertical sense. If this is the case care would have to be taken to insure that corresponding directions in the vertical plane as well as the horizontal plane were compared.

To test this hypothesis a series of observations were made and are tabulated in TABLE 9 and in figure 4.11. Since there is no vertical circle on the Cunningham Laser Theodolite the vertical angles are approximate and refer to an elevation above an unknown reference elevation. Each microammeter reading is the mean of four readings.

The results of this test show that the laser is not symmetrical in the vertical plane. This explains the difference between the readings made by Sprinsky and those of the author.

This lack of symmetry need not be an insurmountable problem. The results of the second measurement of a horizontal angle demonstrates that we can get accurate results as long as corresponding points on the response curves of the two targets are compared.

TABLE 9. - - Observations to determine if the laser beam is symmetrical in the vertical plane.

Direction	Microammeter Reading Reference	Elevation 6!4	9!6	12!8	16!0	19!2
00	5.0	5.5	4.4	5.6	4.7	5.0
02	5.0	5.6	4.7	6.0	5.0	5.0
04	5.0	6.6	6.0	7.1	5.0	5.0
06	5.0	8.6	9.7	10.0	6.0	5.1
08	5.4	12.7	15.1	13.2	6.1	5.1
10	6.0	16.0	17.8	14.9	7.1	5.2
12	6.5	18.6	16.2	16.2	9.6	6.2
14	6.5	15.1	14.6	20.7	12.6	6.7
16	5.9	12.1	15.0	21.5	12.1	6.1
18	5.2	11.2	14.9	17.0	8.1	5.0
20	5.1	9.3	11.0	9.9	5.5	5.0
22	5.0	6.7	6.0	6.0	5.0	5.0
24	5.0	6.0	4.7	5.2	5.0	5.0

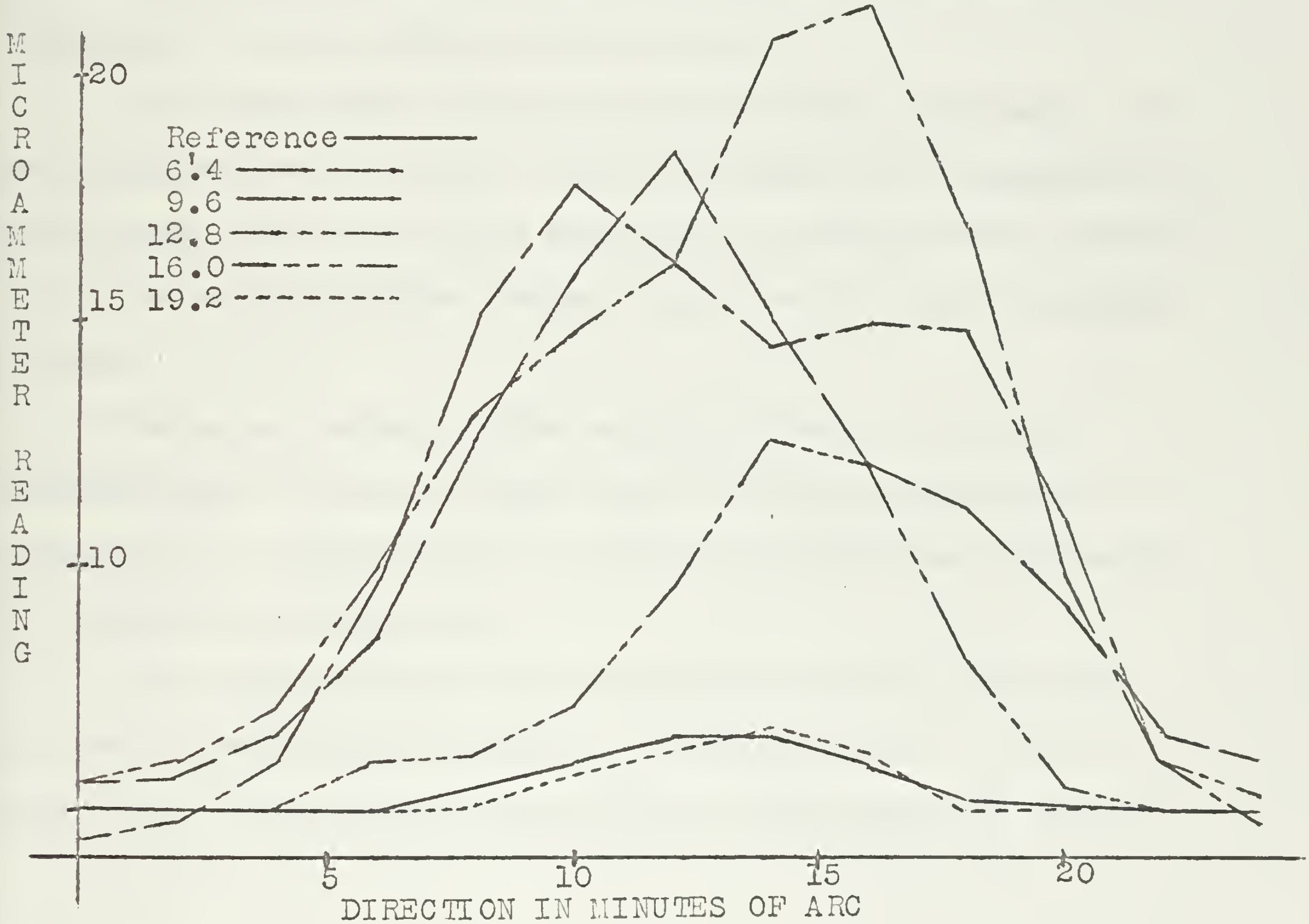

Fig. 4.11. Various laser return signals for selected vertical Angles.

CHAPTER 5

SUMMARY

5.1. ERRORS

Several sources of errors have been determined in the course of the work on this paper. The following is a summary of these errors with my recommendations on how to eliminate, or at least minimize, these errors.

The error caused by uneven graduations of the horizontal circle and the seconds drum can be minimized by advancing the circle and the drum between repetitions.

The error caused by dislevelment of the instrument can be minimized by including a precision level as a component of the system, and using field procedures to minimize the effect of a lack of parallelism between the level and the horizontal circle.

The error caused by the horizontal axis not being perpendicular to the vertical axis of the instrument can be eliminated by changing face. The laser theodolite will also be required to change face.

Lost motion in the laser theodolite can be minimized by always moving the instrument in one direction. Prior to deploying a field party this cause of error should be deter-

mined numerically, and if beyond some arbitrary limit, a new instrument provided, or the instrument repaired.

Operator's errors in achieving coincidence or reading the seconds drum can only be minimized by selecting, or training, experienced personnel.

The error caused by a lack of symmetry of the laser beam in the horizontal and vertical planes will be the most difficult to eliminate. Looking at page 53 it can be seen that this error can amount to minutes of arc. If the two targets and the theodolite lie in a plane that can be defined by moving the laser only with the horizontal controls this will be no serious problem. This must be considered to be not the general case. The problem can be solved, or at least reduced to acceptable limits, by several simultaneous approaches. The laser selected should have as near a symmetric beam as can be ecconomically procured. The laser beam width must be as narrow as we can get it. The latter will also increase the effective range of the system. Finally, the vertical circle should be read along with the horizontal circle at each direction. Subsequent repetitions should be at different vertical settings. If there is a disagreement among the readings indicating that a systematic error is present, the observations should be repeated.

The error caused by fluctuations of the microammeter with factors other than direction can be large, but do not

seem to be as serious as those caused by the lack of symmetry of the laser beam. The author's experience is that these errors are compensating. TABLE 7 on page 50 is an example. Directions were taken on either side of peak value, and meaned. Then the angle was formed by subtracting the two mean directions to the two targets. The readings at 20 μamps. serve as an example. Variations in the directions ammounted to as much as twenty seconds, but the largest residual of the final angle formed from the directions was six seconds. These fluctuations, of course, should be reduced. The internal optics of the laser must be clean. The alignment of the end mirrors must be stable with changing conditions. Regulated DC-DC converters may be required.

The last source of error does not arise from the instrument. This is refraction. This problem will be minimized by a large number of repetitions.

5.2. FLEXIBILITY OF OPERATION

This section will deal with flexibility of operation. This is actually outside the scope of this thesis, but an instrument that is only good under laboratory conditions is of marginal utility for field operations.

The filter for use with the laser should match the laser. Captain Sprinsky proposed the idea that a neutral density filter could be used. This would, however, defeat the idea of a filter to eliminate the picking up of background light.

The wiring boxes built by Mr. Cunningham were fine for testing a prototype instrument, but must be watertight for field use. The connections to the laser and PM tube must also be watertight.

Several times during this work considerable delays were encountered because there was no ammeter or voltmeter available. As long as we need new wiring boxes we may as well include an integral ammeter and voltmeter. One of each will be required in any event, and we may as well save the time needed for making connections.

The whole alignment system of the LAS-101 should be scrapped. This system may work well on an optical bench, but it is useless in the field.

In the author's opinion, the alignment should have the end mirrors attached and supported by the plasma tubes, to reduce the relative motion between the end mirrors and the plasma tubes. The area of the laser between the end mirrors and the plasma tubes should be filled with an inert gas, and thermally controlled. This should give the alignment system stability that it now lacks.

5.3 FINAL SYSTEM ENVISIONED

As a conclusion to this thesis I will present my idea of a final system. The system will be portable by helicopter in one trip. The equipment and men will be put down on the peak of a hill or mountain in the center of

the area to be surveyed. The helicopter will then take about fout men to set up target, retrodirective mirrors at separated points, and clear the area in the vicinity of the points. They will then set up aerial targets. The first night's readings would be to these four targets. The next night's observations would be to one of these targets, and to three new targets. This could be repeated until the area is covered. If we assume a range of fifty miles, we would need an accuracy of one part in two hundred fifty thousand in range, and an angular accuracy of one and two tenths seconds, to get an accuracy of one foot in the coordinates of a point. This is certainly adequate for photogrammetric uses. The advantage of this is that the errors would not be cumulative through the net. This would cover an area of no less than seventy eight thousand square miles. Another big advantage would be that much less advance planning would be required. Finally, there would be no "least squares" adjustment of the network, so that the final computations could be done in the field. This is particularily true if we include a small computer that has been programmed beforehand. This procedure could be done with a standard theodolite and one of the microwave systems for range, but then we may need multiple remote stations. This is because we would need a remote instrument at each station. Another possible alternative would be to separate ranges and bearings. This would have the

disadvantage that the time to complete the survey may be excessive. The last problem will be locating the target in the field of view of the laser. This will require some auxiliary system that is outside the scope of this thesis.

BIBLIOGRAPHY

1. Reese, Jerry Thomas. "Electronic Surveying with the Laser." Unpublished Master's Thesis, Department of Geodetic Science, Ohio State University, 1965

2. Cunningham, Leslie Lee. "A Laser Theodolite." Unpublished Master's Thesis, Department of Geodetic Science, Ohio State University, 1965

3. Troup, Gordon. Masers and Lasers. London: London Methuen and Company Ltd, 1963

4. Heavens, O.S. Optical Masers. London: London Methuen and Company Ltd, 1964

5. Schawlow, A.L. "Optical Masers", Scientific American, 204, 52, 1961, cited by, Laboratory Experiments with Coherent Light, (Electro Optics Associates, Palo Alto, California, 1965)

6. LAS-101, 3-65, Advertisement Pamphlet, Electro Optics Associates, Palo Alto, California, March, 1965.